A DENDROCLIMATIC ANALYSIS OF THREE INDIGENOUS TREE SPECIES, SOUTH ISLAND NEW ZEALAND

A thesis submitted for

the degree of

Doctor of Philosophy

in the

Department of Botany,

University of Canterbury

by

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University of Canterbury

1983

TO FIONA

HIGH COUNTRY WEATHER

Alone we are born
    And die alone;
Yet see the red-gold cirrus
    Over snow-mountain shine.

Upon the upland road
    Ride easy, stranger:
Surrender to the sky
    Your heart of anger.

James K. Baxter

ABSTRACT

The main aims of this study were to assess the potential of three indigenous New Zealand tree speices, *Libocedrus bidwillii*, *Nothofagus menziesii* and *N.solandri*, for dendroclimatological analysis, to develop tree-ring chronologies from these species and to use the chronologies to reconstruct palaeoclimates.

As a prerequisite to chronology development, the annual nature of *Nothofagus solandri* growth was investigated. Results showed that shoot and radial growth occurred during the summer months only and were closely linked to the course of temperature at this time. Growth ring formation in *N.solandri* was annual.

Thirty-three tree-ring chronologies from the three species were developed from six areas in the South Island; Craigieburn Range, Castle Hill and Flock Hill Basins, Whitcombe Valley, Landsborough Valley, Hollyford Valley and Murchison Mountains. Timberline *Nothofagus menziesii* and *N.solandri* chronologies were the most sensitive to environmental factors, assumed to be climatic (having high mean sensitivity and large common variance values), while *N.solandri* chronologies from bluff sites and subalpine *Libocedrus bidwillii* chronologies were less sensitive. With increasing altitude *N.solandri* chronologies became more sensitive, the most sensitive chronologies being developed from trees growing close to, but not forming, the alpine timberline.

Climatic analysis of the chronologies showed that the timberline *Nothofagus menziesii* and *N.solandri* chronologies were strongly associated with growing season temperature while the three *N.solandri* chronologies developed at montane bluff sites were strongly associated with growing season rainfall. The *Libocedrus bidwillii* chronologies were only poorly associated with climate.

Two reconstructions of past rainfall (for Amberley and Lake Coleridge) and one of riverflow (Hurunui River) were developed using mainly the rainfall sensitive bluff site *Nothofagus solandri* chronologies. The reconstructions extend back to 1840 A.D. Variance explained in calibration ranged from 46% to 60% and in verification from 44% to 66%.

The reconstructed Hurunui riverflow record suggests that riverflows during the period of modern observations may have been higher than the long term average. This reconstruction and future reconstructions from other rivers presents a potentially important source of information for hydro-electric power generation and in irrigation development planning.

New Zealand summer temperature was reconstructed using a grid of seven timberline *Nothofagus menziesii* and *N.solandri* chronologies. 59% of the variance was explained in calibrating the reconstruction while 49% of the variance was explained in verifying the calibration with independent data. Based on this, a reconstruction of summer temperature to 1730 A.D. was developed.

The three climate reconstructions were interpreted in terms of atmospheric circulation patterns affecting New Zealand and were used to verify other proxy evidence for climatic variation during the last 250 years. In the period 1730 to 1900 A.D. cool summers were common in the 1740's, about 1760 and from 1830 to 1860 and were probably periods of increased southwest to west airflows onto the South Island. Canterbury rainfall, reconstructed as below average in the 1850's, also suggested more persistent westerly airflow at this time. Runs of warm summers occurred more commonly about 1780, from 1790 to 1820 and from 1870 to 1890. Northerly airflows were probably more persistent at these times.

It is concluded from the research presented in this thesis that the potential of dendroclimatology as a means to reconstruct past climates in New Zealand is considerable.

ACKNOWLEDGEMENTS

I wish to acknowledge the Forest Research Institute, New Zealand Forest Service, for generous support during this study. Financial assistance during the early stages of this study was provided by the Alpine Processes Group, Ministry of Works and Development and the Botany Department, University of Canterbury (Teaching Fellowship) and is also gratefully acknowledged.

I would like to express my appreciation to Colin Burrows for supervising this thesis. Colin initially interested me in dendrochronology while I was still an undergraduate student and has continued to encourage me in my work. His wide knowledge of, and enthusiasm for, the New Zealand flora and palaeoecology in general has been very useful and has stimulated my interest in a wide range of ecological, botanical and natural history topics.

Special thanks go to Matt McGlone, John Ogden and Jim Salinger for considerable encouragement and many helpful comments and suggestions during this study. They also patiently read through the many pages of thesis that passed their way.

A large number of people have commented on various aspects of this study; I would like to express my appreciation to them. Discussions with Udo Benecke, Murray Cave, Anne Gellatly, Ian McCracken, Mac McLennan, Mauri McSaveney, Jonathan Palmer, Friedrich Röthlisberger, Walter Schönenberger, Tom Veblen, John Wardle and Peter Wardle were most helpful. The many other people who have been helpful in various ways are also thanked.

Alistair Moore and Richard Harper assisted considerably during field work and I would like to thank them for their company, interest and encouragement.

The New Zealand Meteorological Service provided climate records while the Ministry of Works and Development made riverflow data available. Computer programs developed at the Tree Ring Laboratory, University of Arizona and at the Climatic Research Unit, University of East Anglia were used and the help of these organisations in

providing them is acknowledged. The use of equipment at the School of Forestry, University of Canterbury and at the Department of Botany, University of Auckland was of great assistance and is gratefully acknowledged. The New Zealand Forest Service and Department of Lands and Survey are thanked for permission to sample in Craigieburn Forest Park, Arthurs Pass National Park, Mount Aspiring National Park and Fiordland National Park.

Glenys Lamb did a wonderful job typing the thesis.

Finally I wish to express my appreciation to my parents for their continuous support and encouragement during my studies, and to my fiancé, Fiona, whose support and help, especially with drawing figures and proof reading, has been invaluable.

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PART I

CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

Throughout history, climate has played a dominant role in the course of mankind's development. It has been suggested that whole civilizations have disappeared as a result of changing climate (e.g. the Myceneaen and Indus cultures, Bryson 1978) while today mankind is himself altering climate through the addition of carbon dioxide into the atmosphere (Stuiver 1978, Pittock and Salinger 1982). Even in today's technologically developed society, the potential vulnerability of mankind to climate disaster is considerable. Harsh Northern Hemisphere winters and severe droughts in South Australia during the last few years are examples of such vulnerability. Extreme events such as these generate considerable public interest and concern. However, changes in average conditions could have greater social, economic and political impact than extreme events (Maunder 1978). For example, if several successive years of drought occurred in North America or Russia, massive grain shortages could result. The consequences of such shortages would be far-reaching.

An ability to accurately predict climate during the next five, ten or fifty years would enable mankind to plan for potential future changes. Such predictions are, however, difficult to make (Ratcliffe 1978) and need to be based on a good understanding of past climatic variation (Lamb 1977). Many techniques have been developed to study past climates (see review in Lamb 1977) and include the study of oxygen isotope variations in ice cores, pollen analysis and the dating of glacial deposits. Proxy records of climate developed with these and other techniques differ in spatial coverage, length, and ability to resolve variations at different time scales. For example, pollen data provide millenia-long climatic records but the smallest resolvable time scale is tens to hundreds of years. It is also often difficult to accurately calibrate such proxy evidence and their climatic meaning can be unclear (Burrows 1982). Recently, however, calibration of pollen data against modern climate has been undertaken (e.g. Sauchs et al. 1977). A technique developed in recent years which has shown considerable potential involves using climatically dependent variations

in tree growth ring widths as proxy evidence for past climate. Considerable success has been achieved using tree-rings to reconstruct annual variations in climate during the last millennia (Hughes et al. 1982). The potential exists to extend tree-ring climatic reconstructions back several thousand years (LaMarche 1974a).

Growth rings, which are usually produced annually, can serve as records of environmental conditions influencing growth at the time of formation. Growth rings are layers within the xylem of trees, resulting from cell division in the vascular cambium. In temperate latitudes this cambial activity is not continuous throughout the year, being dependent on seasonal changes in climate. In spring, with rising temperatures and freely available soil moisture, fusiform and ray initials in the vascular cambium start to swell. Active cell division soon follows, forming the earlywood (large thin-walled cells) towards the inside of the cambium. As the growing season proceeds, physiological processes within the tree gradually change, eventually causing the formation of small, thick-walled, latewood cells. Growth ceases with the onset of unfavourable conditions during autumn. In years when conditions during the growing season are unfavourable for growth (e.g. temperatures are cool or drought occurs) growth is restricted. Biomass accumulation is reduced and a narrow growth ring formed. In favourable seasons, other factors constant, a wide growth ring is formed. The patterns of wide and narrow growth rings can be used as proxy climatic records; the analysis of these patterns is termed dendrochronology.

1.2 DENDROCHRONOLOGY AND DENDROCLIMATOLOGY

1.2.1 Historical Perspective

It was through the work of A.E. Douglass that the study of tree growth rings became established. Sunspot activity and its possible influence on climate initially interested Douglass. In looking for a proxy for the scanty and discontinuous climatic data available, he reasoned that trees might serve as records of past climates (Douglass 1914). His basic argument was,

(i) growth rings of trees measure food supply,

(ii) food supply depends largely on the amount of available moisture, especially when moisture is limiting (as in semi-arid regions),

(iii) so in such regions the rings are likely to provide a measure of rainfall.

Initial errors in counting were overcome by matching (crossdating) ring series between different trees. Douglass (1914) could identify the same pattern of wide and narrow rings in *Pinus ponderosa** trees 81 km apart in Arizona, United States. He reasoned that crossdating could be used as a chronological tool to identify the exact calendar year in which a ring was formed and that the ring width pattern represented a record of environmental conditions prevailing during the life of the tree. He demonstrated that, from the available climate records, growth in *P.ponderosa* was related to rainfall during the preceding winter. He went on to relate tree growth, as a climatic record, to solar activity. Subsequent papers (1919, 1928, 1936) extended this work.

Most early interest in dendrochronology was centred around the use of the technique as an archaeological dating tool. For example, Douglass (1921, 1929), working with *Pinus ponderosa* from Arizona, was able to date prehistoric Pueblo Indian dwellings by crossdating living and dead wood specimens. Much of this work is documented in the early volumes of Tree-Ring Bulletin. Two students of Douglass, Waldo Glock and Edmund Schulman, extended tree-ring analysis to other problems, species and sites during the 1940's and 1950's (Glock 1955, Schulman 1956). Schulman's work culminated in the discovery of 4000 year old *Pinus aristata* trees in California, United States (Ferguson 1969). Dendrochronology developed more slowly elsewhere. The work of Huber in the 1940's firmly established tree-ring research in Europe (Eckstein 1972). In recent years more emphasis has been placed on the use of tree-rings for reconstruction of past climates. Harold Fritts, Val LaMarche and others at the Tree-Ring Laboratory, University of Arizona, have provided the basis for the recent applications of dendrochronology to palaeoclimatic research.

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* Nomenclature for indigenous New Zealand plants is after Allan (1961) and Moore and Edgar (1970). Nomenclature of other plants follows that used in the reference in which the plant is discussed.

1.2.2 Principles of Dendrochronology

Several basic principles underlie dendrochronological studies (Fritts 1976, Creber 1977, LaMarche 1982),

(i) Uniformitarian Principle. The physical and biological processes that operate today, linking the environment with tree growth, have operated in the past. Similarly, the types of variation in weather and climate observed today occurred in the past. The validity of this principle is supported from other fields of study (Fritts 1976, p.15).

(ii) The Principle of Limiting Factors. Tree growth is dependent on the most limiting environmental factor(s). Ring sequences can only be crossdated when one or more environmental factors are limiting.

(iii) The Principle of Site Selection and Sensitivity. Site selection is undertaken in order to maximize the effect of the limiting factor of interest in the study. Sites selected are usually close to the margin of the species distribution, where environmental factors strongly limit growth. Such sites produce *sensitive* ring series; large annual variations in ring width are a response to variations in the limiting factor. *Complacent* ring series exhibit little annual variation because the trees grow in less limiting environments.

(iv) The Principle of Crossdating. This is the most fundamental principle of dendrochronology and provides a control in dendrochronological studies. Crossdating is the matching of similar ring width patterns between different trees, allowing the detection of missing and false (intra-annual) rings and hence the accurate assignment of a particular ring to its year of formation. Fritts (1976, p.21) states that; "Crossdating is possible because the same or similar environmental conditions have limited the ring widths in large numbers of trees, and the year-to-year fluctuations in limiting environmental factors that are similar throughout a region produce synchronous variations in ring structure". That crossdating can be achieved is in itself evidence that some limiting environmental factor, through its influence on growth, is common to all the sampled trees.

(v) The Principle of Calibration. This principle involves the correlation of ring widths with various climatic parameters over the period of instrumental climatic records. Extrapolation from these data then allows the reconstruction of palaeoclimates.

1.2.3 Present status

Dendrochronology is a broad term used to describe tree-ring studies in which annual growth rings are assigned to, or assumed to be associated with, specific calendar years (Fritts 1976). There are many subfields of dendrochronology, depending on the focus of the study. Five subfields are discussed below.

Tree-ring dating has been used extensively to date archaeological features, particularly in western North America (e.g. Robinson 1976). In recent years, tree-ring dating of archaeological sites in Europe has proved very successful (Berger 1970, Fletcher 1978, Baillie 1982). Prehistoric sites, buildings and artwork (paintings and sculptures) have been dated. Perhaps one of the most significant contributions of tree-ring dating to archaeology (and to other fields) has been calibration of the radiocarbon timescale. Radiocarbon dating of accurately crossdated wood specimens has shown that fluctuations in atmospheric Carbon-14 content have occurred in the last 8000 years (Damon et al. 1974, Stuiver 1982). As a consequence, it is now known that radiocarbon years do not necessarily coincide with chronological years. Appropriate corrections can be made for some of this secular variation (e.g. Stuiver 1982, McFadyen 1982) but for some time-periods (especially the last 400 years) this is not possible and considerable uncertainties are present in radiocarbon dates (Röthlisberger et al. 1980).

The use of tree-rings in an ecological context has been widespread. Much of this research has been directed towards tree-age estimation and the analysis of changes in growth rates and recruitment (Ogden 1980). The literature on dendroecology is immense and includes the assessment of the impact of insect defoliation on trees (e.g. Morrow and LaMarche 1978, Brubaker 1978), the identification of tree flowering years (e.g. Holmsgaard 1955), reconstruction of forest history (e.g. Henry and Swan 1974, Oliver and Stephens 1977) and aging of fire events (e.g. Druce 1957, Romme 1982, Hernstrom and Franklin 1982), as well as the determination of forest population age structures (e.g. Clayton-Greene 1977, Ogden 1978a, Herbert 1980, Miller and Cummins 1982). Most of this work

has not involved crossdating. A detailed review of some of the problems associated with the use of tree-rings in studying forest dynamics is presently being prepared (Norton et al. in prep).

Dendrogeomorphology involves the use of tree ages and changes in growth rates to date a variety of geomorphic events. A detailed review of this subject is presented by Shroder (1980). A variety of events including earthquakes (e.g. LaMarche and Wallace 1972), glacial advances (e.g. Lawrence and Lawrence 1965, P. Wardle 1973a), snow avalanches (e.g. Burrows and Burrows 1976, Conway 1977), vulcanism (e.g. Lawrence 1954, Druce 1966) and lake level fluctuations (e.g. Cameron 1957) have been dated.

A relatively new application of dendrochronology is to the field of air pollution research. Nash et al. (1975) noted a reduction in ring width at the time two copper smelters commenced operation but could not definitely prove a cause-and-effect relationship. Symeonides (1979) found that variations in tree growth rates and in the heavy metal content of tree-rings could be used to construct a record of atmospheric pollution in the study area.

The fifth subfield, dendroclimatology, is the main concern of this thesis. Dendroclimatology is the use of climatically dependent variations in annual tree growth rings to reconstruct past climates. Unlike many other sources of palaeoclimate proxy data, tree-rings can be dated to the exact calendar year and can be calibrated against modern climate.

The initial work of Douglass in reconstructing past rainfall (Douglass 1914 and later papers) and extensive studies by Schulman (1956) established dendroclimatology in the early days of tree-ring research. However, it is only since the development of high-speed computers that this subfield has started to expand rapidly. The work of Fritts (1976) and LaMarche (1974a, 1978) was instrumental in dendroclimatology's modern expansion. Today several research groups are actively involved worldwide (see papers in Hughes et al. 1982). The development of transfer function techniques (calibrating ring width against modern climate, verifying this, and then reconstructing past climates based on the calibration relationship) (Fritts et al. 1971) has allowed the reconstruction of past climates with considerable reliability.

Classically, dendroclimatology has used variations in ring width as the basis for reconstructing past climates (e.g. Fritts et al. 1979, Brubaker 1980, Jacoby and Cook 1981, LaMarche and Pittock 1982, Briffa et al. 1983). Work by the research groups of Polge (1970), Parker (Parker and Henoch 1971) and Schweingruber (Lenz et al. 1976, Schweingruber 1982) has shown that variations in ring density (especially latewood density) have many advantages over ring widths for reconstructing past climate. Several reconstructions have been developed (Schweingruber et al. 1978, 1979, Conkey 1982). The use of other growth ring components has received less attention. Hill (1982) was able to relate the spacing of parenchyma bands to rainfall. Eckstein and Frisse (1982) have investigated the relationship between vessel area and climate.

A further application of tree-rings in reconstructing past climates has been through the measurement of isotope levels in growth rings (Long 1982, Wigley 1982). Several different isotopes have been investigated, the most important being Oxygen-18 (Burk and Stuiver 1981), Carbon-14 (Suess 1971, Stuiver 1980) and Carbon-13 (Pearman et al. 1976, Grinsted and Wilson 1979, Mazany et al. 1980). However, the reality of the link between climate and isotope concentration has yet to be proven conclusively (Wigley et al. 1978, Wigley 1982).

The expansion of dendroclimatological research in recent years has resulted in the development of several tree-ring chronology grids, designed primarily for palaeoclimatic reconstruction. Such grids are necessary to reliably reconstruct past climates (see Section 7.3.2). Papers in Hughes et al. (1982) summarise the present status of dendroclimatology worldwide. Dendroclimatological techniques have only recently been applied to the Southern Hemisphere (LaMarche 1975). The work of Val LaMarche and his co-workers has seen the development of tree-ring chronology grids in South America (32 chronologies), Australia (17) and New Zealand (21) (LaMarche et al. 1979a,b,c,d). Recent research in Australia is discussed in Ogden (1978a,b, 1981, 1982), Morrow and LaMarche (1979), Dunwiddie and LaMarche (1980a), Duke et al. (1981), Campbell (1982), LaMarche and Pittock (1982) and Perlinske (1983) and in South America by Holmes et al. (1979) and Holmes (1982). The technique of dendroclimatology has proved more difficult to apply to Southern African trees (Lilly 1977, Curtis et al. 1978, Dyer and Curtis 1978, Dyer 1982); so far only one tree-

ring chronology has been developed (LaMarche et al. 1979e, Dunwiddie and LaMarche 1980b).

1.3 DENDROCHRONOLOGY; A NEW ZEALAND PERSPECTIVE

The history of dendrochronological research in New Zealand can be divided into two main periods; an early period with largely negative results and a modern period during which considerable progress has been made. Reviews of New Zealand tree-ring research are included in Dunwiddie (1979), Norton (1979), Burrows and Greenland (1979) and Ogden (1982).

1.3.1 The early period

Oliver (1931), Lokerbie (1950) and Batley (1956) estimated the ages of archaeological features based on the ages of living trees. The first attempts to construct chronologies were also for archaeological dating (Bell 1958, Bell and Bell 1958, Cameron 1960, Scott 1964). Various conifer species were examined but with little success. P. Wardle (1963a) found significant fluctuations in the ring widths of *Dacrydium cupressinum* trees in Fiordland but did not attempt to correlate them with climate. The regular occurrence of conspicuous latewood bands (marker rings) in the same sequence in several *D.cupressinum* trees in South Westland has been correlated with cool autumn temperatures (Franklin 1969). Carter (1971) produced a short, dated *Nothofagus solandri* chronology from a site in the North Island, although it is probable that his chronology was not accurately crossdated (Norton 1979). Carter (1971) was unable to develop chronologies with other species. Several species on Mount Ruapehu (North Island) and near Lake Tekapo (South Island) were examined by Scott (1972) but failure to crossdate trees or obtain significant and meaningful correlations with climate lead him to conclude that "dendrochronological techniques will be extremely difficult to apply in New Zealand" (Scott 1972, p.558). Wells (1972) found *Podocarpus hallii* in Central Otago to be an insensitive dendroclimatic indicator. Little correlation was found between ring widths of *Libocedrus bidwillii* trees in the Waikato district and climatic parameters (Clayton-Greene 1977).

Tree-rings have also been used to date geomorphic features. Variations in the levels of closed basin lakes have been determined using tree-ring counts (Cameron 1957). Lawrence and Lawrence (1965) and P. Wardle (1973a) have used tree ages to give minimum dates for glacial moraines. Recent volcanic eruptions on Mount Egmont have

been dated using tree-rings by Druce (1966). He considered that he was able to identify years of reduced growth resulting from scorching at the time of the eruption and aged eruptions in this way. Topping (1971) has also used ring width sequences for dating volcanic events. Tree-ring sequences have been used to date avalanche events (Conway 1977).

Tree-rings have been used most commonly in New Zealand to age forest trees, primarily to determine forest tree population age structures. Early work suggested that tree-ring formation was not necessarily annual in many New Zealand trees (Hutchison 1926, Lloyd 1963) but more recent research has shown that annual growth rings occur in many species (P. Wardle 1963b, Franklin 1969, Wells 1972, Jansen and Wardle 1971, Herbert 1977, Dunwiddie 1979, Ogden and West 1981, Palmer and Ogden 1983, Chapter 2). An extensive literature has developed in which tree-rings have been used to determine forest tree ages (e.g. P. Wardle 1963b, 1978, 1980a, Clayton-Greene 1977, Herbert 1980, Bathgate 1981, Johnson 1982, June 1982, McSweeney 1982, Appendix 1).

1.3.2 The modern period

As part of an extensive study of the forests of the Longwood Range in Southland, Bathgate (1981) examined variations in tree-ring widths in *Dacrydium cupressinum*. Although this study sampled several hundred trees, the resulting chronologies and their palaeoclimatic interpretation must be viewed with considerable caution. There are three main reasons for this,

(i) Crossdating was not undertaken. Rather, ring widths were assumed to be annual and measured in ten-year groups. This is questionable, especially in a species which frequently has vague ring boundaries, false rings and lobate growth and is generally difficult to age (Dunwiddie 1979, Katz 1980).

(ii) An inflexible standardisation procedure was used that does not take into account any individual tree growth rate variations. The "universal" age-curve used was assumed to apply to all trees.

(iii) The relationship established between ring width and climate was vague, being based on a correlation between five-year running means of temperature and ring width. Examination of the actual

data shows few clear agreements between the two series, except a general increase in values from 1853 to 1977.

For these reasons it is considered that more work is needed before Bathgate's chronologies can be used to reconstruct palaeoclimates. This study is not considered further here.

Since the mid 1970's, modern dendrochronological techniques, which have been successfully applied to mesic forests elsewhere in the world, have been used in New Zealand. Three research groups have been involved. The initial impetus came from the staff of the Tree-Ring Laboratory, University of Arizona, who, as part of a Southern Hemisphere sampling program (LaMarche 1975), visited New Zealand in 1977 and 1978 and developed the first properly crossdated and replicated tree-ring chronologies (Dunwiddie 1978, 1979, LaMarche et al. 1979c). 21 tree-ring chronologies were developed from seven species *(Libocedrus bidwillii, Phyllocladus alpinus, P.trichomenoides, P.glaucus, Dacrydium colensoi, D.biforme, Agathis australis)* from sites throughout New Zealand (Fig. 1.1). A further 13 species were sampled.

An ongoing research programme under the guidance of John Ogden of Auckland University has concentrated on the dendroclimatological potential of *Agathis australis*. The aim of the project is to develop long tree-ring chronologies from living and dead (bog) trees, to be used for palaeoclimatic reconstruction. Seven chronologies have so far been developed from throughout the northern part of New Zealand (Fig. 1.1), although these have not yet been published. Initial response function analysis suggests that considerable climatic information is present (John Ogden and Jon Palmer, personal communication January 1983). Some preliminary results are presented in Palmer (1982) and Palmer and Ogden (1983).

The final area of research has been in the South Island and is presented in this thesis. In an earlier study (Norton 1979, 1981a), two *Nothofagus solandri* chronologies were developed and preliminary climatic analysis undertaken. The study showed the potential of this species as a palaeoclimatic indicator. In conjunction with the work undertaken in this thesis, Aston (1982) has also developed two *N.solandri* chronologies and presented preliminary climatic interpretations. These chronologies are discussed further here.

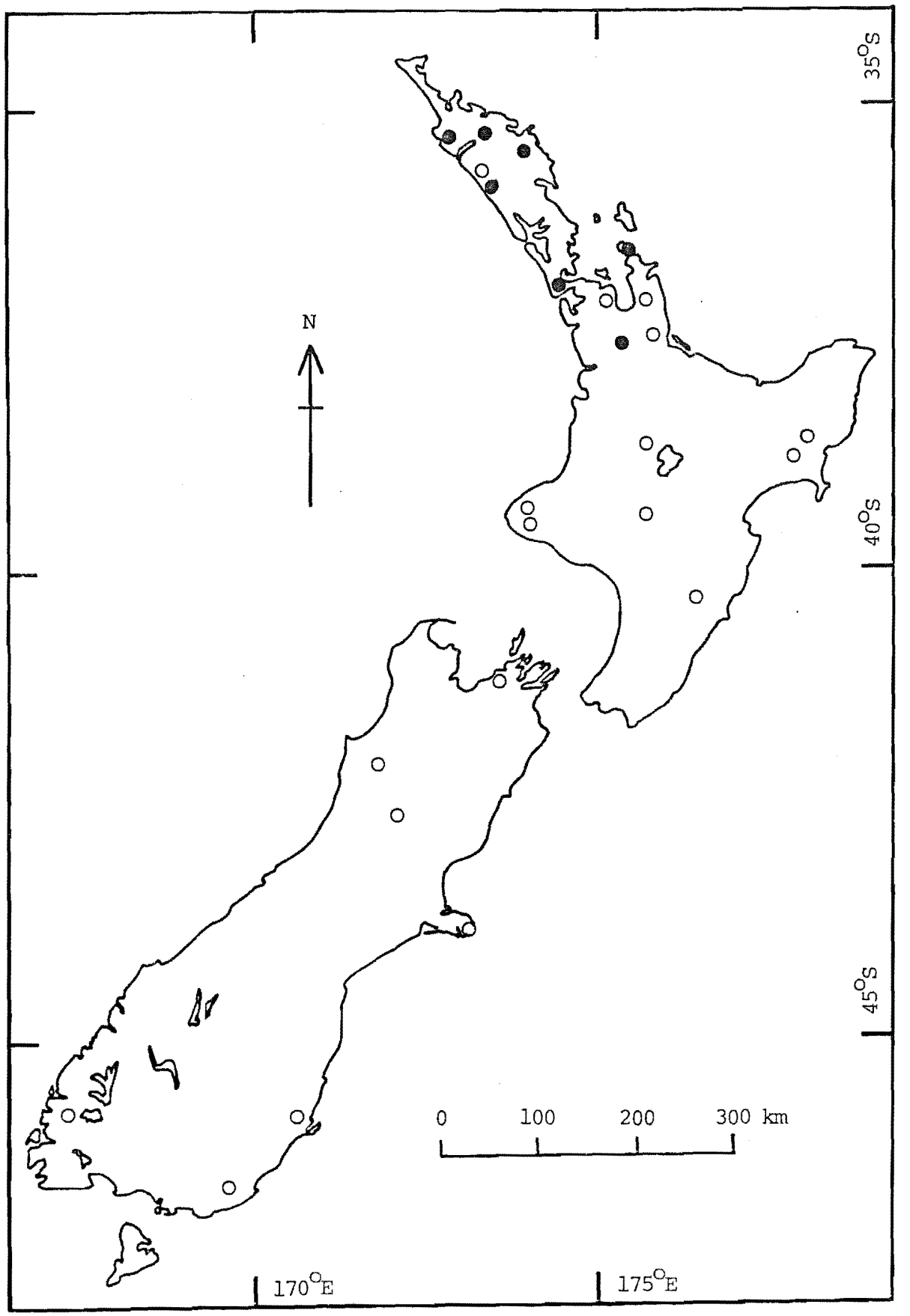


Figure 1.1 Location of tree-ring chronologies developed by LaMarche et al. (1979c) (O) and John Ogden (personal communication) (●).

1.4 CLIMATE

1.4.1 Concepts and definitions

Dendroclimatology is the use of climatically dependent variations in annual tree growth rings to reconstruct past climates. Definitions of climate and other related terms are given below.

(i) Weather. The term weather is used to describe the complete atmospheric conditions at a given time. Weather constitutes several elements including temperature, rainfall, humidity, cloudiness, sunshine, wind and pressure (Lamb 1972). Similar weather conditions can persist for several hours or days if the elements of the weather continue to behave in a similar way.

(ii) Climate. This is the sum total of the weather experienced at a given place for a defined period such as a year or several years (Lamb 1972). It includes both average and extreme conditions. Normal or average climate can be defined in different ways. For example, the range of observations that fall within one standard deviation either side of the mean for a given period. Mean climate is used here for comparing climate during different time periods. Climate always refers to a specified time period.

(iii) Climatic variation. Climate is recognised as being continually variable and can change in several ways (Berger 1981). The most obvious is through a change in average conditions but climatic change can also occur when variability about a constant mean changes. Much controversy has centred around the question; "What is climatic change?". Climatic change can refer to the increase in mean air temperature in New Zealand since 1950 or to the difference between full glacial and interglacial conditions. Because of the difficulties associated with this term, changes in mean climatic conditions reconstructed here are referred to in terms of climatic variability and the question of whether these do or do not constitute a climatic change is not addressed.

(iv) Microclimate, local climate and regional climate. Mean climate can be measured at different levels; from a global scale to that influencing a single plant. Three levels of climate are

referred to in this thesis, reflecting the expression of climate at differing spatial scales. Each level of climate is dependent on the next level up as well as on the factors that characterise that level.

Microclimate is the sum of the climatic conditions experienced at a particular site and is influenced by aspect, slope, altitude, site topography and vegetation cover.

Local climate reflects local areas which show homogeneous temperature or rainfall anomalies in response to differing weather systems. Salinger (1979b) has divided New Zealand into response areas, each having its own distinctive local climate. The main axial ranges of New Zealand have a pronounced influence on local climate.

When all the different local climates within New Zealand are considered together, the resulting mean values represent the influence of the regional New Zealand climate. Regional climate thus represents the mean influence of the overall atmospheric circulation patterns affecting New Zealand.

(v) Climatic limitation. The interactions between climate and tree growth are complex. Tree growth can occur under a wide range of climatic conditions but when a particular climatic element exceeds or falls below a particular optimum level, growth is restricted; a climatic limitation of tree growth.

Photosynthesis is the primary source of dry matter production in plants and is dependent on several climatic parameters; solar radiation, temperature, wind and moisture are particularly important. Changes in the levels of these factors cause changes in the rate of photosynthesis. For example, as temperatures decline or light levels fall below an optimum level, the rate of photosynthesis is reduced and growth is restricted. Other growth processes (e.g. hormone activity) are also dependent upon climatic conditions.

Reviews of tree-growth-climate interactions in Fritts (1976) and Tranquillini (1979) include examples of climatic conditions under which growth is restricted. Fritts (1976, in

chapter 5) also discusses the various physiological pathways by which climate can limit tree growth.

(vi) "Exceptional" climatic events. Shifts in mean climatic conditions can cause changes in plant growth rates by limitation or promotion of plant growth processes. Extreme, or "exceptional", climatic events can also cause limitation of plant growth but often the limiting mechanism is by physical damage rather than by modification of physiological processes. For example, heavy snowfall can cause considerable canopy breakage with a reduction in the area of photosynthetic tissue and thus reduced growth. The duration of "exceptional" climatic events is usually short, lasting for several hours or possibly several days. Damage to plants can be widespread. Such events occur irregularly, perhaps once every two to five years or less. "Exceptional" climatic events include windstorm, heavy snowfall and widespread frost and are discussed in detail in Section 6.7.1.

1.4.2 An overview of New Zealand climate

As there are several accounts of New Zealand climate available (Maunder 1971, Coulter 1973, Tomlinson 1976a, Salinger 1981, 1982b) only a brief summary is given below. The high mountainous nature of much of New Zealand and the ocean locale have an important influence on climate. New Zealand's climate is very much influenced by the predominant westerly airflow. The close proximity to the sea ensures that airflow onto the country is moist and has a moderating influence on air temperature. The pronounced relief provides a barrier to the prevailing westerly winds causing a strong west-east rainfall gradient across the country.

The mid latitude band of westerlies contains a succession of migratory depressions and anticyclones. The positions of these and the speed with which they cross the New Zealand region determines our day to day weather. Discussions on this subject are given in Maunder (1971) and Salinger (1981). However, the overall climate of New Zealand is influenced by larger scale circulation systems. Recent research on these (Trenberth 1975, 1976a, 1976b) has shown that distinct circulation modes occur, the nature of which determines the distribution of temperature and rainfall anomalies across New Zealand (Salinger 1980b, 1980c).

Two main atmospheric quasi-periodicities affect New Zealand: variations in the strength of the tropical Pacific Walker Circulation and the Quasibiennial Oscillation. The Walker Circulation is a global circulation pattern particularly prominent over the Pacific Ocean. A longitudinal ocean temperature gradient between warm tropical waters north of New Zealand and cold waters off the Peruvian coast drives this equatorial east-west circulation system (Trenberth 1976b). Variation in the strength of the Walker Circulation is known as the Southern Oscillation. When the Walker Circulation is strong, and the Southern Oscillation index therefore high, easterlies are common over New Zealand (e.g. during 1971, 1973 and 1974, Trenberth 1977, Salinger 1981). When it is weak, and the Southern Oscillation Index low, westerlies prevail (e.g. 1982-1983 summer, personal observation). Changes in the mode of the Southern Oscillation have a periodicity of about 3 to 6 years (Trenberth 1976b).

The Quasibiennial Oscillation reflects the relative importance of southerly and northerly airflows across New Zealand and has a regular occurrence. All even years from 1954 to 1970 and all odd years since 1970 have experienced predominantly northerly airflow while alternate years have been more southerly (Trenberth 1977). However, as the strength of these airflows has varied, some periods have been characterised by more northerly or more southerly airflow than other periods. The causes of the Quasibiennial Oscillation are unknown although changes in the differences between the rates of land and sea heating may be important (Trenberth 1975).

The mode of the Southern and Quasibiennial Oscillations influences the airflow across New Zealand and hence the climatic anomalies experienced. Airflows from the northeast to southeast bring rain to eastern areas while more westerly airflow brings rain to the west. Salinger (1980b) discusses these patterns in more detail. Temperature variations are more synchronous throughout New Zealand than rainfall variations (Salinger 1979a) and are dependent on the trajectory of airflow, particularly in the last few thousand kilometres before reaching New Zealand. Warm periods occur when northwest to eastnortheast airflow, passing over the milder East Australian Ocean current, is dominant. Cooler periods occur when airflow is from the west to southwest, passing over the colder waters of the circumpolar West Wind Drift.

1.5 AIMS OF STUDY

The possibility of using tree-ring chronologies to reconstruct New Zealand palaeoclimates gave the initial impetus for this study. Interpretation of such reconstructions would considerably improve our understanding of climatic variation during the last few hundred years. Several aims underly this study,

(i) To evaluate the usefulness of *Nothofagus* species for developing well replicated and crossdated tree-ring chronologies.

(ii) To assess the suitability of different sites for chronology development, especially with respect to altitude.

(iii) To construct a widespread grid of tree-ring chronologies suitable for palaeoclimatic reconstruction.

(iv) To identify the climatic components most limiting to tree growth at each site and hence to identify which chronologies offer the most potential for reconstructing these components for periods prior to instrumental climate records.

(v) To assess the feasibility of using the tree-ring chronologies developed here for reconstructing past New Zealand climates.

(vi) To present preliminary New Zealand palaeoclimatic reconstructions based on dendroclimatic techniques.

1.6 SUMMATION OF CHAPTERS

In Chapter 2 the annual course of shoot and radial growth in *Nothofagus solandri* trees at different sites is investigated. In Chapter 3, the three species studied *(N.solandri, N.menziesii, Libocedrus bidwillii)* and the sites at which they were sampled are described. The methods used to develop the tree-ring chronologies are discussed in Chapter 4. Chapters 5 and 6 discuss the 33 tree-ring chronologies developed here. Variations in ring width patterns within trees and between tree-ring chronologies at different altitudes are discussed and the presented chronologies compared with those developed elsewhere. The influence of "exceptional" climatic events and non-climatic factors on ring width is also discussed.

The rest of the thesis is concerned with examining the climatic signal in the tree-ring chronologies which are then used to reconstruct past climates. Chapter 7 describes the techniques used to achieve this. In Chapter 8 the climatic signals in the individual tree-ring chronologies are discussed and tree-ring chronology groups with potential to reconstruct palaeoclimates identified. The chronologies are then used in Chapter 9 to reconstruct recent New Zealand palaeoclimates. The reconstructions are discussed and compared with other evidence of recent New Zealand palaeoclimate in Chapter 10. The application and usefulness of dendroclimatology in New Zealand, and future research needs, are also discussed in this last chapter. The main conclusions of this study are summarised in Chapter 11.

The first two Appendices describe research undertaken in conjunction with this thesis. This work provides useful ecological background information to the research undertaken in the main part of the thesis. In Appendix 1, the population dynamics of subalpine *Libocedrus bidwillii* forests is discussed and in Appendix 2, the nature of *Nothofagus solandri* tree growth at the alpine timberline investigated. In Appendix 3, a computer program developed for use in this thesis is presented. The 33 tree-ring chronologies are tabulated and plotted in Appendix 4. Appendices 5, 6 and 7 present data and other information referred to in the main text.

CHAPTER TWO

NOTHOFAGUS SOLANDRI PHENOLOGY AND GROWTH

2.1 INTRODUCTION

Tree growth in areas of seasonal climate is confined to periods of favourable conditions. In mountain regions, favourable conditions occur mainly during the warmer summer months (Tranquillini 1979), while in areas with a pronounced dry season, growth is mainly confined to the wet period (Ogden 1981). This periodicity of tree growth results in the formation of distinct xylem bands (growth rings). The annual formation of these growth rings is an essential prerequisite for any dendrochronological investigation (Stokes and Smiley 1968, Fritts 1976) and in many temperate regions, phenological studies have shown that growth ring formation is annual (see reviews in Fritts 1976 and Tranquillini 1979). However, the occurrence of wet and dry seasons in tropical regions may not necessarily follow an annual pattern, with the formation of more than one growth ring per year (e.g. Duke et al. 1981).

The formation of annual growth rings has been shown conclusively for only a few indigenous New Zealand trees (*Agathis australis*, Palmer 1982, Palmer and Ogden 1983; *Beilschmeidia tawa*, Ogden and West 1981; *Phyllocladus trichomanoides*, Herbert 1977; *Podocarpus totara*, Wells 1972; and various subalpine shrub and tree species, P. Wardle 1963b).

It has also been shown that growth processes of *Nothofagus* species (mainly *N.solandri*) are largely annual (P. Wardle 1963b, 1971, Bussell 1968, J. Wardle 1970d, Benecke and Havranek 1980a). However, these studies have largely been confined to saplings and young trees and growth in mature trees, similar to those sampled here for tree-ring analysis, has not been extensively examined. The relationship between shoot growth and radial growth has not been closely followed.

This chapter investigates the annual nature of growth ring production in *Nothofagus solandri* trees at three altitudes in the Craigieburn Range, by following the course of shoot extension and radial growth over two growing seasons.

2.2 METHODS

Three sites in the Cass area were selected for study (Fig. 2.1, Table 2.1); two subsites in Sugarloaf Bush are treated together. The subalpine forest site is typical of those sampled in the Craigieburn Range for tree-ring chronology development. At each site, trees of single leader habit, of good form and which are canopy dominants, were selected for study. Tree diameters are mainly between 0.4 m and 0.7 m. Based on age estimates from cored trees in the same area, tree ages of between 150 and 250 years are probable. Trees sampled at the timberline margin are of the coppice and prostrate growth forms (Appendix 2). The vegetation of the two Upper Cass Valley sites is described in Chapter 3 and Appendix 2 and that of Sugarloaf Bush by Burrows and Norton (1982).

A further site at Lake Eyles in Fiordland was also sampled (Table 2.1). Nine trees had dendrometer bands placed on them in November 1981, but only seven of these trees are used in the analysis. The site is described in Appendix 4.

Shoots on five trees in Sugarloaf Bush, six trees at timberline and two trees in subalpine forest were marked during August to October 1980. The junction on a branch of a prominent lateral shoot and a terminal shoot (approximately 10 cm to 20 cm from the terminal bud) was marked with paint. The shoot was then tagged with strips of aluminium to facilitate later identification (Fig. 2.2a). Only shoots exposed to full sunlight for at least part of the day were marked. At Sugarloaf Bush and in the subalpine forest, this involved climbing up into the tree canopies. The distance from the marked junction to the tips of both the terminal and lateral shoots was measured. 284 shoots (both terminal and lateral) were initially measured, but several had to be discarded because of bud death and shoot breakage. 212 shoots, consisting of 100 lateral shoots and 112 terminal shoots, were used in the final analysis.

Various techniques are available for monitoring radial growth in trees (see review in Fritts 1976); dendrographs and dendrometers are the most common. Dendrographs provide a continuous record of diurnal variations in stem size but are expensive and need regular maintenance. Because of this and because of the interest in seasonal

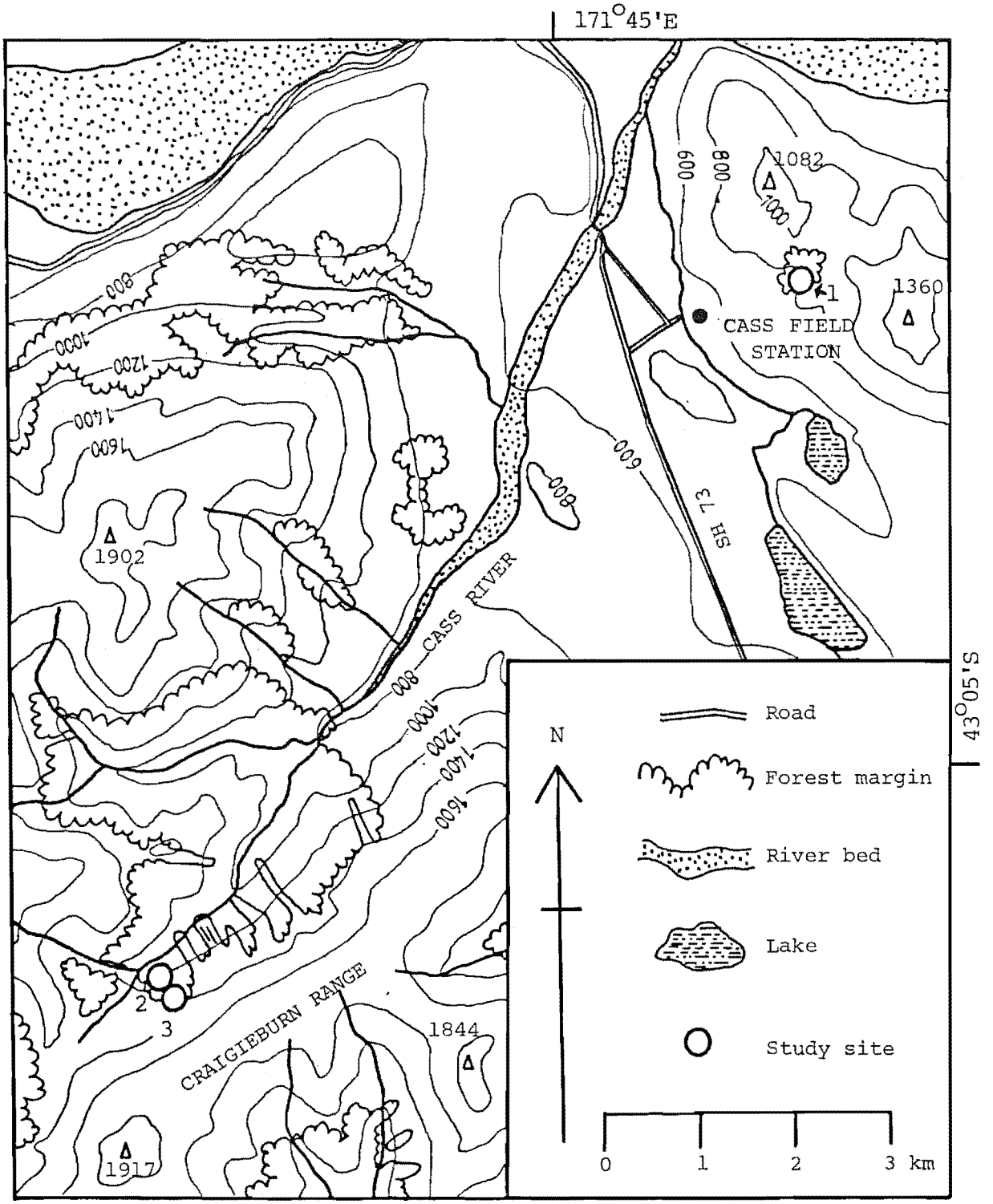


Figure 2.1 Location of the three sites at which Nothofagus solandri phenological observations were undertaken in the Craigieburn Range. 1, Sugarloaf Bush; 2, subalpine forest; 3, timberline.

TABLE 2.1 Summary descriptions of the five sites investigated during the phenological study.

Site name and grid reference (NZMS1 series)	Altitude (m)	Aspect	Stand type	Tree form	Tree height (m)	Number of trees sampled (dendrometers)	(shoots)
Sugarloaf Bush A S66 244173	800	N	closed forest	erect	12-14	4	3
Sugarloaf Bush B S66 245174	800	NW	closed forest	erect	12-14	4	2
Subalpine forest S66 172094	1220-1280	NW	closed forest	erect	8-12	19	2
Timberline S66 173092	1330	NW	marginal forest	prostrate coppice	1-3	0	6
Lake Eyles S140 546387	950	NE	closed forest	erect	12-14	9	0

growth patterns rather than diurnal variations, dendrographs were not used here. Dendrometers, which are cheap, easy to construct, require minimal maintenance and are quick to measure, were used instead.

Dendrometer bands were placed on all selected trees (eight in Sugarloaf Bush and 19 in the subalpine forest) in August and September 1980. The bands consisted of stainless steel strips with a vernier scale (Liming 1957), giving a resolution of 2.5×10^{-3} mm. Tension from a coiled spring held the bands permanently around the trees (Fig. 2.2b). Removal of moss and lichen and smoothing of the bark prior to placement allowed the bands to lie firmly around the tree bole. The bands were placed at breast height.

Maximum-minimum thermometers which had been previously calibrated against one another were placed on one tree in Sugarloaf Bush (at 1 m, 8 m and 12 m) and one tree in subalpine forest (at 1.5 m, 5 m and 7 m). The middle thermometer on both trees was removed after four months as records from these did not significantly differ from the others. Ground thermometers (-30 cm) were placed in subalpine forest and at timberline, but their records are not used because of repeated damage and removal from the ground, possibly by opossums.

The dendrometers, shoots and thermometers were measured at approximately two weekly intervals over the summer and otherwise monthly until June 1982. This time period spanned two growing seasons, 1980-1981 and 1981-1982.

2.3 ACCURACY OF DENDROMETERS

Dendrometer bands are subject to various errors which can affect growth measurements.

(i) Inherent measurement errors occur but are not necessarily very large. The conversion of absolute values to percentages and the averaging of measurements from several trees helps overcome most of these errors.

(ii) Palmer (1982) discussed the possibility of thermal expansion in aluminium dendrometer bands. He concluded that the errors associated with mean dendrometer readings would probably be

Figure 2.2 a Tagged *Nothofagus solandri* shoot at the timberline site.

b A dendrometer band and thermometer placed on a *Nothofagus solandri* tree at the subalpine forest site.

a.

b.

greater than thermal expansion errors. Thermal expansion of the stainless steel bands used here would be less than for aluminium bands and is not considered a problem.

(iii) Another source of unavoidable error results from diurnal fluctuations in tree radius as a consequence of water movement within the tree (Daubenmire 1946). However, this error was reduced as measurements were usually made at a similar time of the day at both sites (around midday). Even if error remained, it would be reduced to insignificance because of the two week interval between measurements; radial change of greater magnitude occurs on this time scale.

The errors discussed are unlikely to have much effect on the measurements made and those errors that do remain will be non-systematic. The results presented here are therefore considered a good representation of radial growth in these trees.

2.4 RESULTS

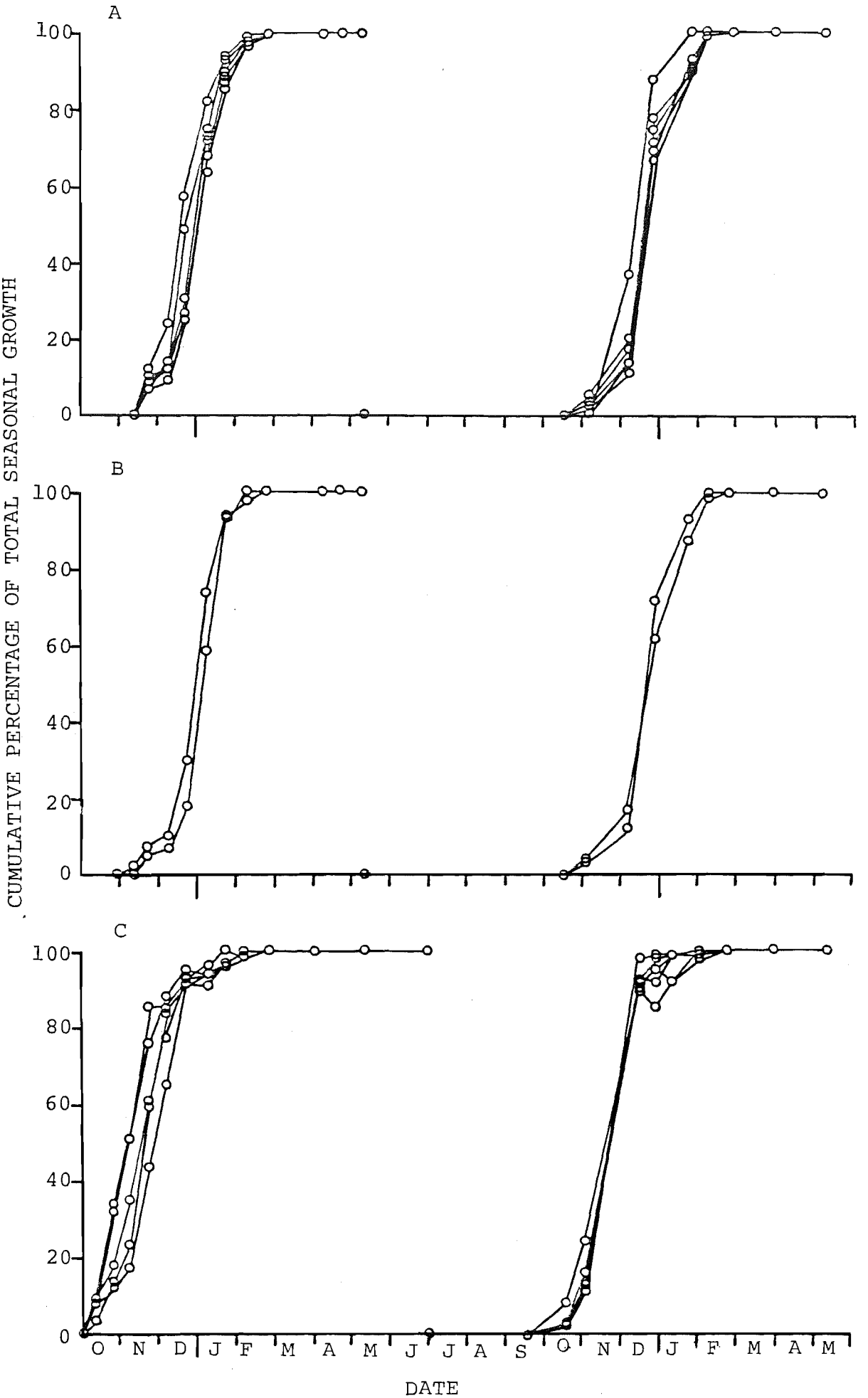
For analysis and interpretation, growth data can either be expressed as percentages of total seasonal growth or as actual growth increments. The former method allows easy comparison of the time of growth at different sites, while the latter allows comparison of differences in actual growth rates. The data can also be expressed as cumulative values (e.g. J. Wardle 1970d) or as mean daily growth rates (e.g. Benecke and Havranek 1980a).

As the main aim of the phenological study was to assess the periodicity of tree growth, growth information was converted from absolute values to percentages of total growth for each growing season. As well as allowing easy comparison between the different sites, and between shoot growth and radial growth, this made calculation of mean daily growth rates easier. However, total growth (in mm) is used to obtain gross comparisons between the sites and the seasons.

2.4.1 Shoot growth

The results of shoot extension are presented for each tree in Fig. 2.3, and the standard deviations for individual trees are given

Figure 2.3 Cumulative mean percentage of total annual shoot growth of *Nothofagus solandri* trees at three sites for two growing seasons. A, timberline, n=6 trees. B, subalpine forest, n=2 trees. C, Sugarloaf Bush, n=5 trees. The mean values and their standard deviations are given in Appendix 5.


A
B
C
100
80
60
40
20
0
CUMULATIVE PERCENTAGE OF TOTAL SEASONAL GROWTH
O N D J F M A M J J A S O N D J F M A M
DATE

in Appendix 5. The shoot growth patterns for all trees are similar within each site. Combined data for each site are presented in Fig. 2.5 and differences between the three sites are apparent. Growth occurred considerably earlier at Sugarloaf Bush than at Cass Saddle in both seasons and interestingly, shoot growth at timberline appears to have been slightly earlier than in the subalpine forest.

Growth for each site was similar in both seasons. At Sugarloaf Bush, shoot growth started in early October; 20% was completed by late October during the first season, but not until early November during the second season. At the subalpine forest and timberline sites, shoot growth started in early November, but 20% of total growth was not completed until mid December. By this time, 80% of shoot growth at Sugarloaf Bush was completed. 80% of total growth at the two high altitude sites was not completed until mid January. In both seasons shoot growth was largely completed at all sites by late February. The total amount of growth was greatest at the lower altitude Sugarloaf Bush site in both seasons, but was similar between the two higher altitude sites (Table 2.2). Terminal shoot growth was greater than lateral shoot growth at all sites in both seasons. Total growth was less at the Sugarloaf Bush site in the second season, but differed little at the other two sites.

TABLE 2.2 Mean total *Nothofagus solandri* shoot growth (in mm± one standard deviation) at each site for two growing seasons.
n = number of shoots measured at each site.

	lateral shoot growth	terminal shoot growth	total shoot growth
Sugarloaf Bush (n = 92)			
1980-1981	55±25	64±28	59±27
1981-1982	39±24	46±28	43±26
Subalpine forest (n = 41)			
1980-1981	26±12	39±20	32±17
1981-1982	20±10	40±31	31±26
Timberline (n = 79)			
1980-1981	24±13	34±19	29±16
1981-1982	29±22	37±25	33±24

2.4.2 Radial growth

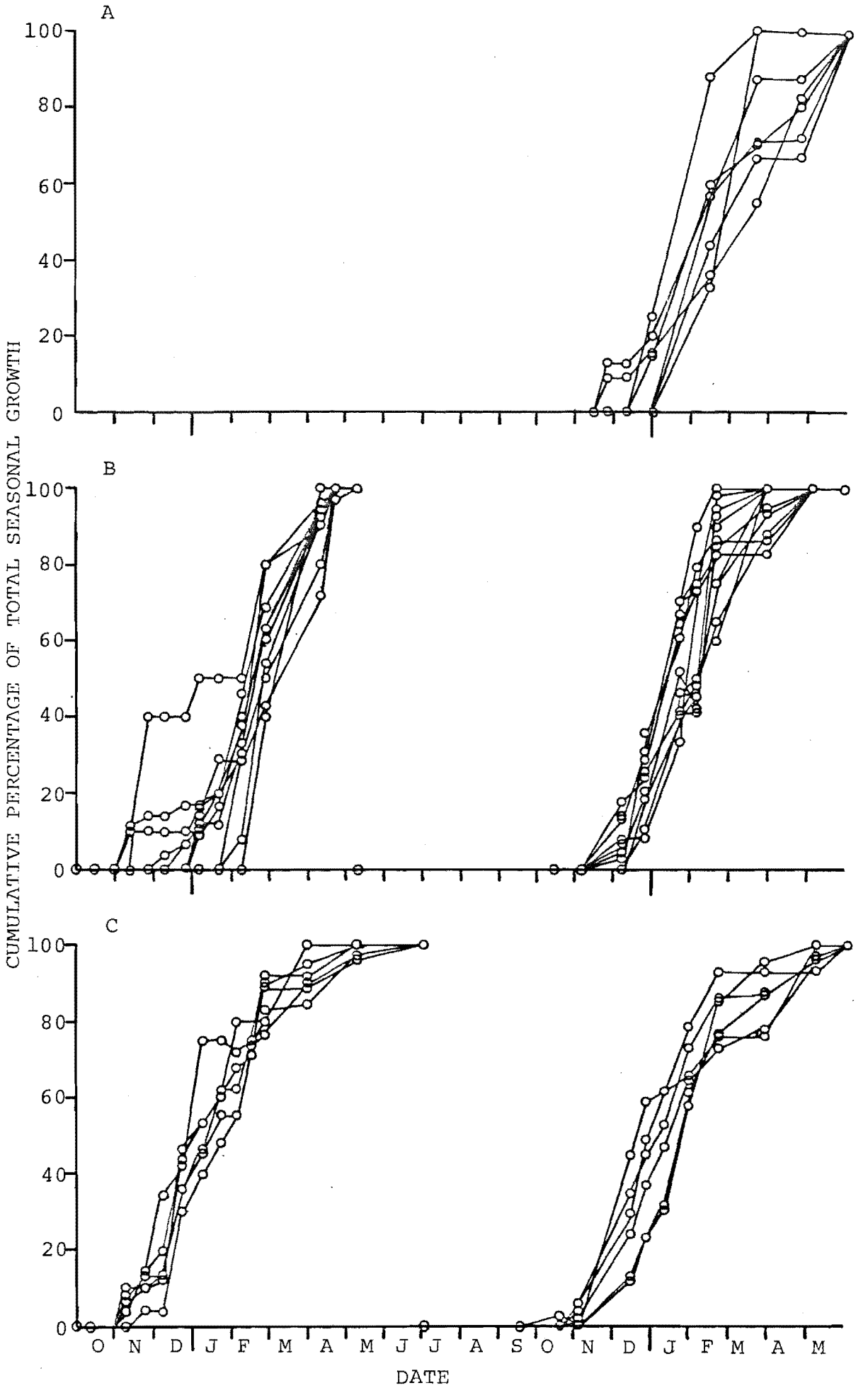
Cumulative radial growth for individual trees is presented in Fig. 2.4. Although considerable variation occurs, the overall trends within each site are similar. In the first season, one tree at the subalpine forest site initially grew rapidly, but did not differ from the others in the second season. Combined data are presented in Fig. 2.5. As with shoot growth, radial growth occurred earlier at the low altitude Sugarloaf Bush site in both seasons. Radial growth at the *Nothofagus menziesii* site was later than the two *N.solandri* sites.

In the first season, radial growth started at the beginning of November at Sugarloaf Bush and 20% was completed by early December, while at the subalpine forest site, 20% of growth was not completed until the end of January. 80% of Sugarloaf Bush radial growth was completed by late February and at the subalpine forest site by late March. Growth ceased first at the subalpine forest site (mid April), but continued at Sugarloaf Bush until May (Fig. 2.5). In the second season, growth started earlier at the Sugarloaf Bush site (October) but as in the first season, 20% was not completed until early December. Growth at the subalpine forest site started in early November and 20% was completed by late December (c.f. late January in the first season). 80% of growth was completed at both sites by late February and ceased towards the end of April at the subalpine forest site, but continued until the end of May at Sugarloaf Bush.

Radial growth at Lake Eyles (Fiordland) started in late November with 20% completed by mid January and 80% by late March. Growth ceased in late May (Fig. 2.5).

The total amount of radial growth at the three sites is given in Table 2.3 and total radial growth was less at the subalpine forest site than at Sugarloaf Bush. The proportional difference in growth at the Sugarloaf Bush and subalpine forest sites was almost identical in both years.

Figure 2.4 Cumulative percentage of total annual diameter growth of *Nothofagus solandri* trees from two sites and *N.menziesii* trees from one site for two growing seasons. A, Lake Eyles (*N.menziesii*), n=7 trees. B, subalpine forest (*N.solandri*), n=11 trees (1980-1981 season) and 13 trees (1981-1982 season). C, Sugarloaf Bush (*N.solandri*), n=6 trees.


A
B
C
100
80
60
40
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0
CUMULATIVE PERCENTAGE OF TOTAL SEASONAL GROWTH
O N D J F M A M J J A S O N D J F M A M
DATE

TABLE 2.3 Mean total *Nothofagus solandri* and *N.menziesii* radial growth (in mm± one standard deviation) at each site for two growing seasons. n = number of trees measured at each site.

	1980-1981	1981-1982
Sugarloaf Bush (n = 6)	1.02±0.25	1.32±0.46
Subalpine forest (n = 13)	0.79±0.51	0.99±0.51
Lake Eyles (n = 7)	-	0.36±0.17

2.4.3 Temperature

Temperature variations recorded by the thermometers at both sites were similar. The record from the 1 m thermometer at Sugarloaf Bush and the 1.5 m thermometer at the subalpine forest site are presented in Fig. 2.7. Small differences between the thermometers on each tree were not significant and could be due to differences between the thermometers, notwithstanding the prior calibration. Temperatures (maximum and minimum) were on average 3^{o}-4^{o}C warmer at Sugarloaf Bush than in the subalpine forest, agreeing well with the annual mean lapse rate of 0.66^{o}C per 100 m calculated for elsewhere in the Craigieburn Range (McCracken 1980). At Sugarloaf Bush, maximum temperatures rose above 20^{o}C during November to April in both seasons, while at the subalpine forest site this was confined to periods during January to March. Minimum temperatures dropped below 0^{o}C between June and September at Sugarloaf Bush, but were below 0^{o}C for all but January, February and March, at the subalpine forest site. In the second season temperatures below 0^{o}C occurred in every month except February at the subalpine forest site.

2.5 DISCUSSION

2.5.1 Commencement of growth

The results presented here clearly show a delay in the commencement of growth with increasing altitude (Fig. 2.5). A delay of approximately four weeks occurred between Sugarloaf Bush (800 m) and the subalpine forest and timberline sites (1220 - 1330 m) in both seasons. *Nothofagus solandri* flowering during the 1980-1981 season was also delayed by about four weeks between Sugarloaf Bush and

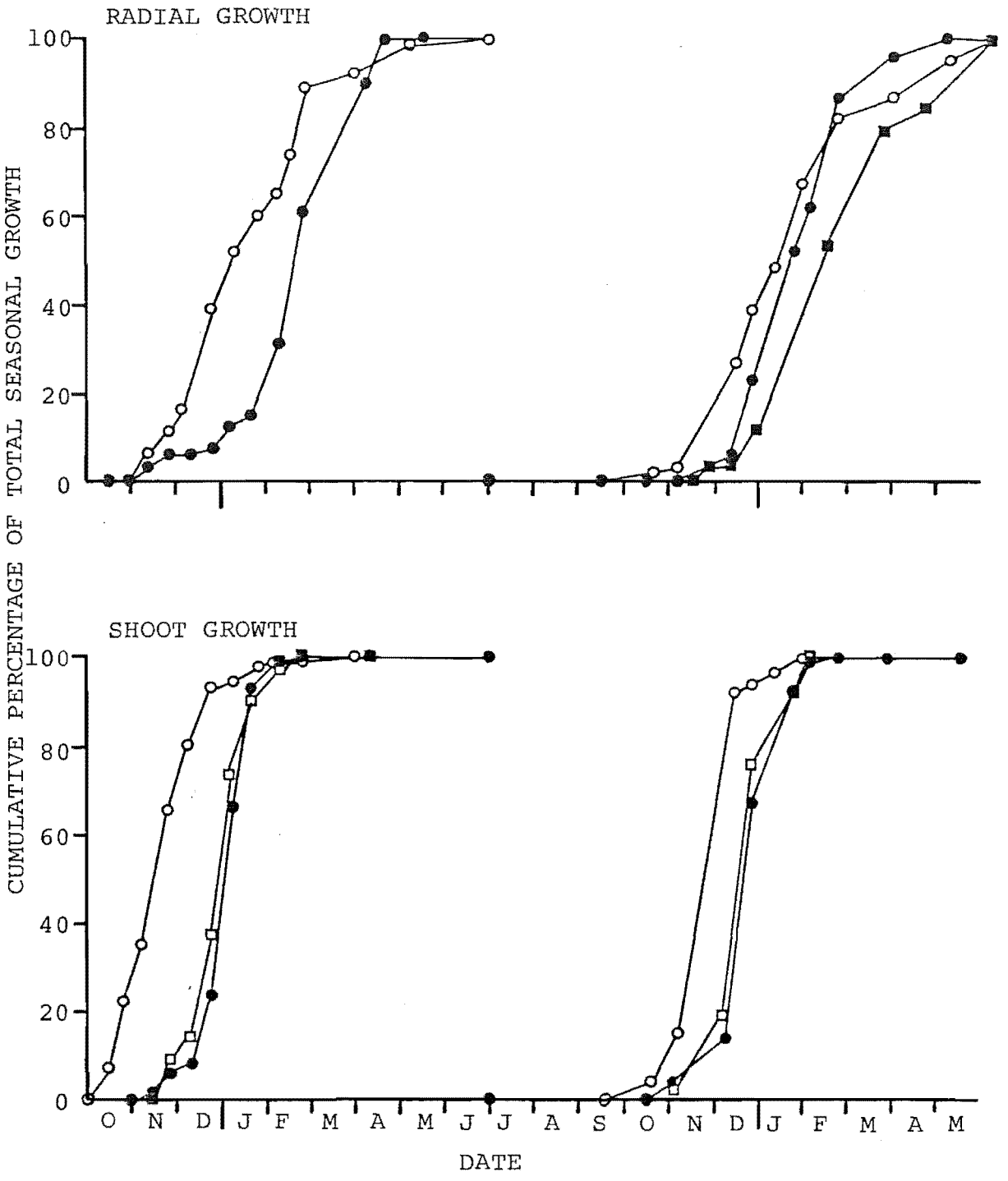


Figure 2.5 Comparison of mean percentage of total cumulative radial and shoot growth for two growing seasons at the following sites:- ● subalpine forest, O Sugarloaf Bush, ■ Lake Eyles, □ timberline. The total muber of measurements made at each site are given in Fig. 2.4 and Table 2.2.

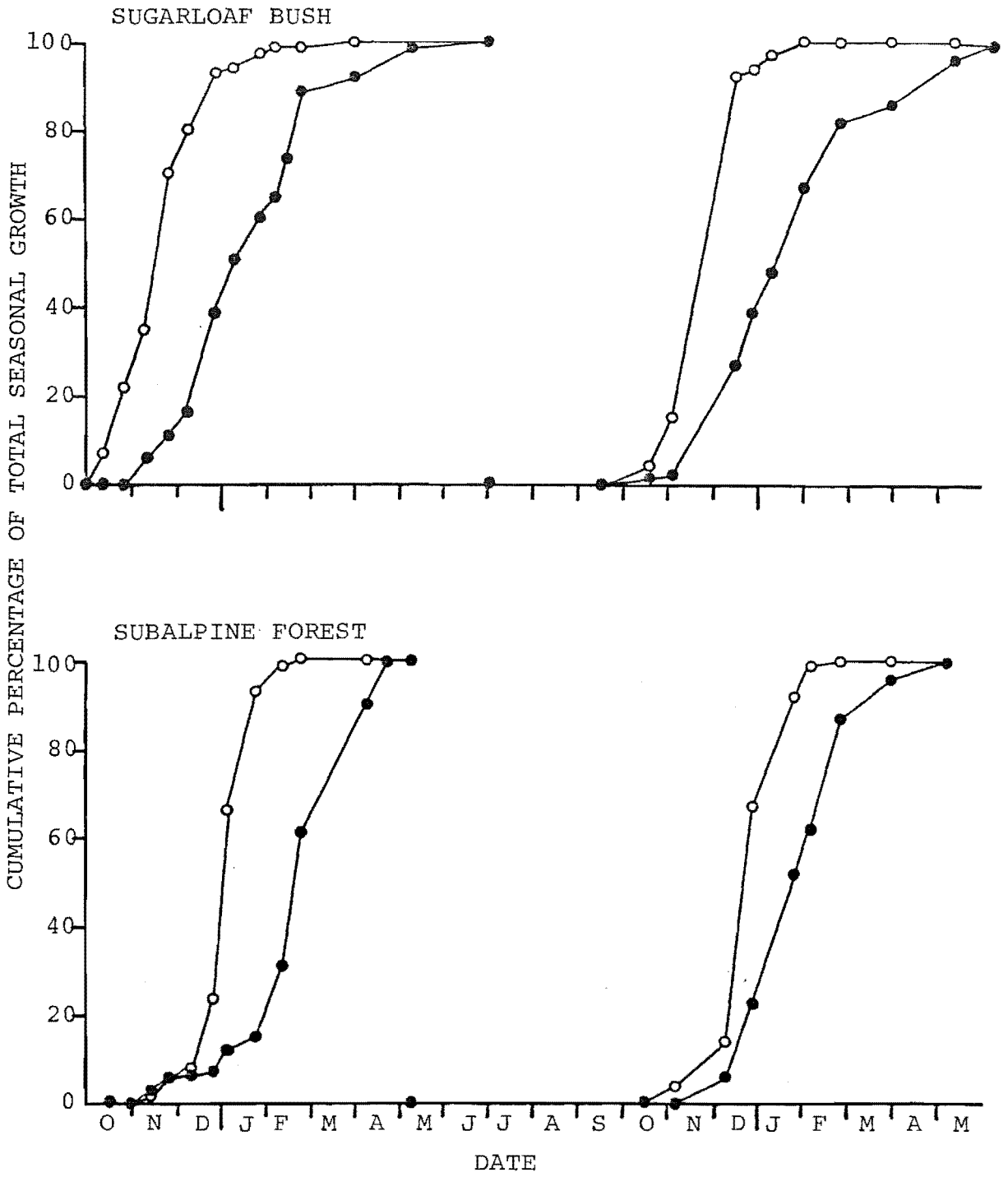


Figure 2.6 Comparison of mean percentage of total cumulative radial growth (●) and shoot growth (O) at the Sugarloaf Bush and subalpine forest sites for two growing seasons. The total number of measurements made at each site are given in Fig. 2.4 and Table 2.2.

timberline. J. Wardle (1970d) and P. Wardle (1971) recorded similar delays in *N.solandri* growth elsewhere in the Craigieburn Range. A delay in growth processes with increasing altitude is common to many species (e.g. Benecke et al. 1978, Benecke and Havranek 1980a) and is the result of altitudinal temperature differences (Tranquillini 1979). For example, during the 1981-1982 season, maximum temperatures above 15°C occurred four weeks later at the higher altitude site and maximum temperatures above 20°C occurred eight weeks later than at the lower site. Delay in the commencement of growth can result in a reduced amount of biomass accumulation, leading to the formation of a narrower growth ring.

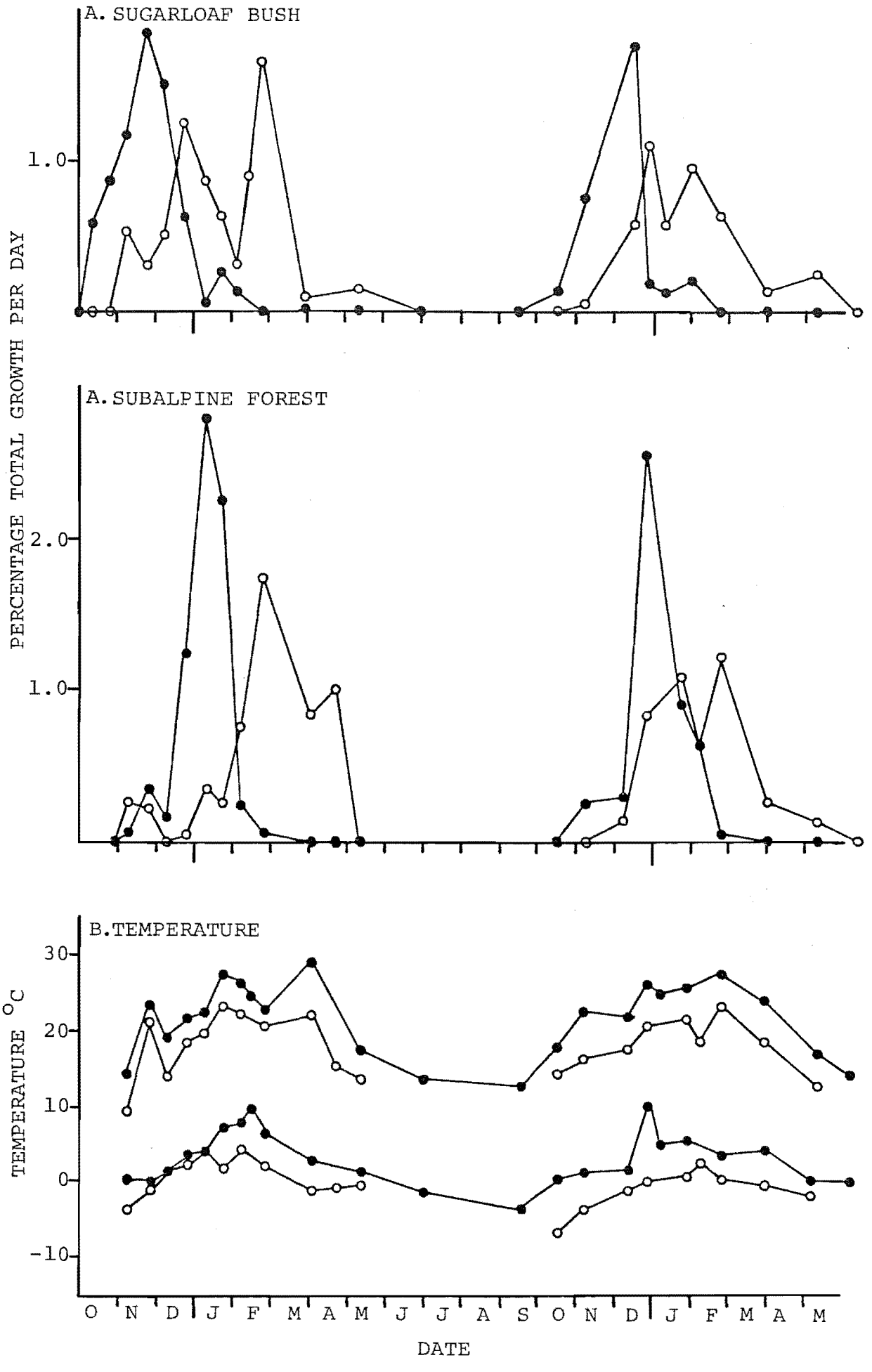
2.5.2 The course of shoot growth

The pattern of shoot extension differs between the two sites (Fig. 2.6 and 2.7). At Sugarloaf Bush, rapid shoot extension occurred immediately after bud burst, while at the subalpine forest site rapid shoot extension was delayed for four weeks after bud burst. A similar delay occurred at timberline. Benecke et al. (1978) have suggested that bud burst does not occur until mean air temperature rises above 5°C and rapid shoot growth is delayed until mean air temperatures reach 7°C-10°C. In many species, the time of bud burst is also influenced by endogenous rhythms, especially those which relate to photoperiod (Tranquillini 1979).

The possibility of factors other than temperature being involved in initiating bud burst in *Nothofagus solandri* trees has been suggested by P. Wardle and Campbell (1976). The factors involved were unknown but it is probable that bud burst in *N.solandri* trees is in part photoperiodically controlled. Immediate shoot growth after bud burst at Sugarloaf Bush suggests that temperatures were already high enough at the time of bud burst for rapid shoot expansion. However, at the higher altitude site, temperatures are still low at the time of bud burst and rapid shoot expansion is delayed for several weeks (Fig. 2.7). The rate of shoot growth at the upper subalpine forest site closely followed temperature. For example, an initial increase in growth in late November 1980 was halted when temperatures dropped in mid December. Growth did not resume again until late December. J. Wardle (1970d) observed a similar delay in the 1967-1968 growing season as a result of an unseasonal November snowfall.

Figure 2.7 A. Pattern of daily radial growth (O) and shoot growth (●), expressed as a daily percentage of total seasonal growth, at the Sugarloaf Bush and subalpine forest sites for two growing seasons. The total number of measurements made at each site are given in Fig. 2.4 and Table 2.2.

B. Seasonal pattern of maximum (upper) and minimum (lower) temperatures at the Sugarloaf Bush (●) and subalpine forest (O) sites for two growing seasons.


A. SUGARLOAF BUSH
1.0
A. SUBALPINE FOREST
2.0
1.0
PERCENTAGE TOTAL GROWTH PER DAY
B. TEMPERATURE
30
20
10
0
-10
TEMPERATURE °C
O N D J F M A M J J A S O N D J F M A M
DATE

Shoot growth at Sugarloaf Bush continued for eight weeks after the initial rapid flush of growth, while only the single flush occurred at the subalpine forest site (Fig. 2.7). This difference could arise because of altitudinally fixed genetical differences. As most leaves are shed in the season after they are produced (J. Wardle 1970d), rapid shoot extension is important for *Nothofagus solandri* to ensure the production of sufficient and fully mature photosynthetic tissue for the next season. The concentration of shoot growth into a single flush is advantageous for trees growing near timberline as it ensures that the leaves are fully mature, even if the growing season is very short.

2.5.3 The course of radial growth

Radial growth does not occur until the majority of shoot growth has been completed. The course of radial growth closely follows that of temperature (Fig. 2.7) and this is most pronounced at the subalpine forest site. Small drops in maximum temperature in mid December and minimum temperature in mid January in the first season, and maximum temperature in early February in the second season, correspond with periods of depressed radial growth at this site (Fig. 2.7). Radial growth at Sugarloaf Bush followed temperature variations less closely. Radial growth at both sites stopped when maximum temperatures fell below 15°C. Benecke and Havranek (1980a) also found a close relationship between temperature and radial growth in *Nothofagus solandri* trees.

The association between radial growth and temperature in trees growing near the alpine and arctic timberline is well documented (see review in Tranquillini 1979), but the influence of other factors (e.g. soil fertility and soil drainage) are also important. Soil moisture shortages in late summer probably limit growth at some timberline ecotone stands in the Craigieburn Range (see discussion in Section 8.5.1). However, the results presented here (especially Fig. 2.7) and also the response functions presented in Chapter 8, quite clearly show the overriding influence of temperature on tree growth.

Temperature would seem to limit radial growth in two main ways. Firstly, the length of the growing season can be influenced by cool temperatures causing either a delay in the commencement of growth or

hastening the cessation of growth. Both are probably important and will have a strong influence on the amount of biomass production and hence the final ring width. Secondly, lower temperatures during the growing season restrict photosynthesis resulting in a decline in dry matter production, leading to reduced radial growth (Tranquillini 1979).

2.5.4 The timing of growth

It is apparent from the results presented here that shoot growth and radial growth occur only during the warmer months. Shoot growth at the start of the growing season is followed by radial growth. The total length of the growing season varies at the different sites, being up to six months near timberline and up to eight months at Sugarloaf Bush. Maximum shoot growth occurs in November and December at Sugarloaf Bush and in January nearer timberline. Radial growth occurs from December through to May at Sugarloaf Bush and from January to April in subalpine forest. No shoot or diameter growth was observed to occur during the winter months.

2.6 CONCLUSIONS

The results presented in this study agree well with those of J. Wardle (1970d), P. Wardle (1971) and Benecke and Havranek (1980a) for other *Nothofagus solandri* stands in the same area. Their studies were, however, largely confined to young trees and saplings. The results presented here extend phenological observations to mature trees. The main points of this chapter are listed below.

(i) Both shoot and radial growth occur later in trees near timberline than at lower altitudes.

(ii) Shoot growth is completed before radial growth.

(iii) The commencement of growth appears to be both temperature and day length dependent.

(iv) The course of shoot growth and especially radial growth is closely linked to temperature.

(v) Radial growth in subalpine forests, similar to those sampled here for tree-ring chronology development, occurs mainly during January, February and March.

(vi) There is no shoot or radial growth during the winter months and growth ring formation is annual in *Nothofagus solandri*.

PART II

CHAPTER THREE

STUDY SITES AND SPECIES

3.1 SAMPLING STRATEGIES

Fritts (1976) and more recently LaMarche (1982) have discussed in some detail the underlying principles and concepts of dendrochronology as these relate to sampling strategies. Sampling strategy (at the species, site and tree level) is critical as it determines the quality of the tree-ring record developed and hence its usefulness for palaeoclimatic reconstruction. The main aim of sampling is to produce tree-ring series containing the maximum amount of climatic information possible and for this reason sampling is not random. Instead species, sites and trees are chosen using recognised criteria which have the aim of maximising the climatic signal in the tree-rings. In the present study, species and site selection was helped considerably by the results of earlier investigations by Dunwiddie (1979) and Norton (1979).

The important criteria for species selection are that the growth rings are annual and distinct, that the trees live to an old age, that growth is responsive to climate and that crossdating is possible. In New Zealand the genera *Agathis*, *Dacrydium*, *Libocedrus*, *Nothofagus*, and *Phyllocladus* have good potential for dendrochronological studies (Ogden 1982) and species from each of these genera have been crossdated successfully (Dunwiddie 1979, Norton 1979). The ability to crossdate is in itself evidence of synchronous growth ring formation and of some regional (probably climatic) controlling factor, although some non-climatic factors (e.g. flowering and insect damage) can mimic climate effects (see Section 6.7). Because of the known dendrochronological potential of *Libocedrus* and *Nothofagus*, species from these genera have been investigated in this study.

Libocedrus bidwillii was chosen because of its already proven dendrochronological ability (Dunwiddie 1979), because of the controversy surrounding its population dynamics (P. Wardle 1978, Veblen and Stewart 1982, Appendix 1) and because it occurs in the so-called "beech gap" in the central South Island where *Nothofagus* species are largely absent. *Nothofagus solandri* has also been shown to have good potential for dendrochronology (Carter 1971, Scott 1972, Norton 1979) and was

chosen because it occurs widely in the South Island and grows at both temperature (alpine timberline) and aridity (dry montane bluffs) limits of forest growth. Although *N.menziesii* has not been used previously in dendrochronological studies, it was chosen for study as, like *N.solandri*, it forms timberline in the subalpine zone and it was considered that it should also be responsive to temperature at such sites. Furthermore, *N.menziesii* trees are thought to live to about 600 years, a much greater age than *N.solandri* (P. Wardle 1967). It has been suggested that growth rings of all three species are annual (P. Wardle 1963b, 1967). The main dendrochronological characteristics of these species are shown in Table 3.1.

Site selection was based on three main criteria; proximity to the climatic limits of the species, site homogeneity and the lack of recent site disturbance. All three species occur in subalpine forest near the upper limits of woody plant growth and both *Libocedrus bidwillii* and *Nothofagus solandri* have been successfully crossdated in this zone previously (Dunwiddie 1979, Norton 1979). Sites as uniform in aspect, slope, drainage, parent material, soils and floristic composition of vegetation as could be found, were sampled. Sites that showed evidence of recent disturbance by windthrow, avalanche, rockfall and other factors were rejected. Site selection was also strongly influenced by access. The Craigieburn Range has easy access, mostly within four hours' walk of the road. The Whitcombe and Landsborough Valleys are more isolated and access was facilitated by the use of helicopters. The Hollyford Valley sites were either close to the main road or near good walking tracks, but access to the Murchison Mountains involved both helicopter and boat trips. Visits to both the Whitcombe Valley and the Murchison Mountains were made possible because other research was being conducted in these areas by the Ministry of Works and Development (Alpine Processes Group) and the New Zealand Wildlife Service (Takahe project).

3.2 SPECIES INVESTIGATED

3.2.1 *Libocedrus bidwillii* Hook.f.

The genus *Libocedrus* (Cupressaceae) is confined to the Southern Hemisphere with three species in New Caledonia and two species, *L.bidwillii* and *L.plumosa*, endemic to New Zealand (Allan 1961). The genera *Papuacedrus* in New Guinea and *Austrocedrus* in South America

TABLE 3.1 Known dendrochronological characteristics of *Libocedrus bidwillii*, *Nothofagus menziesii* and *N.solandri*.

	Libocedrus bidwillii	*Nothofagus menziesii*	*Nothofagus solandri*
Maximum tree age	600 years[1]	600 years[2]	300 years[3]
Annual growth rings	probably[1]	probably[1]	yes[3]
Ring boundary	slightly distinct to distinct[4]	moderately distinct to distinct[4]	moderately distinct to distinct[4]
Limiting habitats	subalpine forest[1]	alpine timberline[1]	alpine timberline & montane bluffs[3]
Previous crossdating	yes[5]	-	yes[6]
Circuit uniformity	variable[5]	-	good[6]
Chronologies developed	yes[5]	-	yes[6]

Notes:
1. P. Wardle 1963b
2. P. Wardle 1967
3. J. Wardle 1970d
4. Meylan and Butterfield 1978
5. Dunwiddie 1979
6. Norton 1979

seem related in appearance and ecology to *Libocedrus* (P. Wardle 1973b). *L.plumosa*, a geographically restricted species not occurring south of the northern part of the South Island, was found to have poor ring clarity and circuit uniformity (Dunwiddie 1979) and was not sampled here.

L.bidwillii (pahutea, kawaka) can grow to a height of 20 m; in sheltered localities it has a tall conical form while in exposed sites it is stunted and often windflagged. The branchlets are distichous (more flattened in juvenile plants) and have imbricate leaves (usually 3 mm or less long). The trees are monoecious. Trees up to 700 years old were observed in this study and may possibly grow to greater age.

The wood anatomy of *Libocedrus bidwillii* has been described by Patel (1968) and Meylan and Butterfield (1978). The growth rings are distinct (Fig. 3.1a), comprising tracheids and axial parenchyma cells with uniseriate and occasionally biseriate rays. Resin canals are absent. Small cells with thick walls occur in the latewood.

Libocedrus bidwillii is a distinctive component of many montane and subalpine forests south of latitude $36^{\circ}50'$ and is especially prominent in high rainfall areas. *L.bidwillii* grows in a variety of plant communities (Cockayne 1928, Elder 1962, P. Wardle 1977, Johnson et al. 1977, Veblen and Stewart 1982). In the South Island the following communities are common (personal observation and C.J. Burrows personal communication January 1983),

(i) Small (up to about 2 ha), relatively pure stands in valley heads.

(ii) Intermingled with other species including species of *Olearia, Senecio, Dracophyllum, Archeria* and *Coprosma*,and *Metrosideros umbellata, Weinmannia racemosa* and *Podocarpus hallii*. *L.bidwillii* trees may occur singly or in groups. This community type is widespread, occurring near the eastern coast (Banks Peninsula, Mount Cargill), in the eastern flanks of the Southern Alps (e.g. upper Rakaia Valley) and in the western ranges of the Southern Alps (Fig. 3.1b).

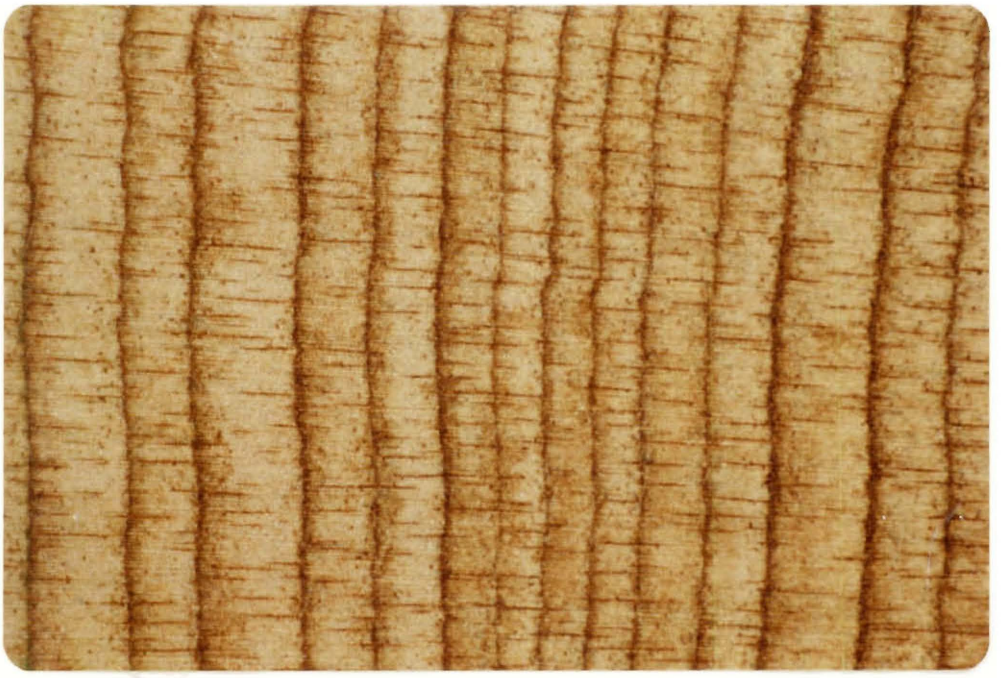


Figure 3.1a *Libocedrus bidwillii* growth rings (approximately 20X natural size).

Figure 3.1b Typical mixed subalpine forest with *Libocedrus bidwillii* emergent over a canopy of *Dracophyllum*, *Olearia* and *Archeria*. *Hoheria glabrata* is in the foreground. Danger Gully subsite, TRK site, Cropp River Valley, Westland. Photo - January 1980.

(iii) Valley floor sites in or at the margin of mixed conifer-angiosperm forest. Accompanying species include *Podocarpus hallii*, *Dacrycarpus dacrydioides* and *Nothofagus fusca*. Some sites are adjacent to frost flats.

(iv) In subalpine *Nothofagus* forest, both east and west of the main divide.

(v) Scattered in scrub and low-tree-covered semi-pakihi (swampland) in Westland.

(vi) Marginal around lakes and bogs where *L.bidwillii*, usually with *Leptospermum scoparium*, some *Dacrydium* species and *Phyllocladus alpinus*, forms a narrow band surrounded by forest.

Little has been published about the ecological requirements and life history of *Libocedrus bidwillii*, although its distribution is well documented. Recent research by Clayton-Greene (1977), Veblen and Stewart (1982) and here (Appendix 1), indicates that this species regenerates to form groups after some form of disturbance to the previous vegetation. Disturbance by slips, windthrow and debris deposition are important in many areas and regeneration can also occur after fire. Although *L.bidwillii* seedlings will grow in full shade, they establish and grow best in the open or under light shade; in some areas regeneration is confined to the forest margin (e.g. on Banks Peninsula, personal observation).

3.2.2 *Nothofagus menziesii* (Hook.f.) Oerst.

Nothofagus (Fagaceae), the Southern Beeches, occur in temperate South America, New Zealand, Australia, New Caledonia and New Guinea. Four species are endemic to New Zealand (Allan 1961); *N.fusca*, *N.menziesii*, *N.solandri* and *N.truncata*. *N.menziesii* (silver beech) is phylogenetically separated from the other New Zealand *Nothofagus* species and is closely related to the Australian *N.cunninghamii* (P. Wardle 1967). Trees up to 30 m tall occur in low altitude forests but decrease in size with increasing altitude. The leaves are coriaceous and approximately 6-15 mm long and 5-15 mm wide, with double-toothed margins and usually glabrous. *N.menziesii* trees are monoecious.

The wood anatomy of *Nothofagus menziesii* has been described by Meylan and Butterfield (1978). The growth rings are distinct (Fig. 3.2a) and consist of vessel members, fibres and axial parenchyma with

Figure 3.2a *Nothofagus menziesii* growth rings (approximately 20X natural size).

Figure 3.2b Monotypic *Nothofagus menziesii* forest looking east from Kea Flat, Landsborough River Valley, to Mount Jackson (2470 m) on the main divide of the Southern Alps. Photo - February 1982.

uniseriate, biseriate and occasionally multiseriate rays. Although vessels are distributed throughout the growth ring they are more numerous and larger in the earlywood. A row of large vessels is commonly present at the start of each growth ring. Reduction in cell size and increase in wall thickness is slight in the latewood, but vessels are distinctly smaller and less common.

The ecology, life history and distribution of *Nothofagus menziesii* described by Poole (1950), P. Wardle (1967) and Manson (1974) is summarised briefly here. In the North Island, *N.menziesii* is abundant in montane and subalpine forests of the southern and eastern ranges while in the South Island it is common in northwest Nelson, north and south Westland, Fiordland and coastal Southland and Otago. Scattered stands also occur in some drier eastern areas (Wells 1972). *N.menziesii* is absent from central Westland and Stewart Island. The extinction of *Nothofagus* species from central Westland is thought to have occurred during the last (Otiran) glaciation (P. Wardle 1964, Burrows 1965). Subsequent migration patterns have not resulted in the re-establishment of *Nothofagus* in this area. *N.menziesii* forms timberline where *N.solandri* is absent (Fig. 3.2b) and occurs down to sea level in south Buller, Westland and Fiordland. Pure *N.menziesii* forests are predominantly subalpine. Elsewhere *N.menziesii* is usually codominant with a wide range of species including *Nothofagus* spp., *Podocarpus* spp., *Libocedrus bidwillii, Dacrydium cupressinum* and *Beilschmeidia tawa*. In mature forests, *N.menziesii* regenerates best under canopy gaps created by windthrow or the death of an old tree, but some regeneration also occurs under closed canopies. *N.menziesii* has the ability to colonise new rock surfaces. Although *N.menziesii* seedlings are light demanding they are less so than those of *N.solandri*.

3.2.3 *Nothofagus solandri* (Hook.f.) Oerst.

Nothofagus solandri (mountain or black beech) is closely related to *N.fusca* and *N.truncata* and hybrids occur frequently (Cockayne 1926). *N.solandri* trees can grow to a height of 25 m, but are considerably reduced in stature in exposed sites. The entire margined elliptic-oblong to ovate-triangular leaves are usually less than 15 mm long, coriaceous and with white tomentum below. *N.solandri* is monoecious and protandrous.

The wood anatomy of *Nothofagus solandri* has been described by Meylan and Butterfield (1978). The growth rings are distinct (Fig. 3.3a)

Figure 3.3a *Nothofagus solandri* growth rings (approximately 20X natural size).

Figure 3.3b Monotypic *Nothofagus solandri* forest looking south from above the west branch of the Cass River to Logos Hill. The Logos Hill altitudinal transect sites are on the ridge descending to the left. Hamilton Peak (1917 m) is in the distance above Cass Saddle (obscured). Photo - February 1981.

consisting of vessel members, fibres and axial parenchyma with uniseriate and biseriate rays. The vessels are distributed throughout the ring but are larger and more numerous in the earlywood. A row of large vessels is commonly present at the start of each growth ring. Cells in the latewood are small and thick-walled and vessels small and uncommon.

The ecology, life history and distribution of *Nothofagus solandri*, described in detail by J. Wardle (1970a,b,c,d), is only summarised here. *N.solandri* is particularly common in the forests of the central North Island and eastern South Island where it is often the only tree species present. It also occurs in the north and southwest of the South Island. *N.solandri* forms timberline over much of its range, especially in the drier eastern areas (Fig. 3.3b). *N.solandri* is usually absent from low altitude high rainfall forests and is absent from much of the central South Island (see Section 3.2.2) and Stewart Island. It seems that *N.solandri* is more tolerant of low rainfall, high altitude, low soil fertility and poor soil drainage conditions than most New Zealand tree species. However, it is a poor competitor with most other tree and shrub species when conditions are more favourable. Regeneration of this light demanding species usually occurs after the formation of canopy gaps, where previously suppressed seedlings are released and grow quickly into the canopy. However, in some circumstances, regeneration can occur under a closed canopy.

3.3 SITES INVESTIGATED

3.3.1 Craigieburn Range

The Craigieburn Range lies in inland Canterbury some 20-30 km east of the main divide of the Southern Alps, forming part of the watershed between the Rakaia and Waimakariri Rivers (Fig. 3.4). Sites sampled were in the Hamilton, Harper, Waimakariri, Cass, Craigieburn and Broken River catchments (Fig. 3.5). The mountains rise to over 2000 m; their rocks are of indurated interbedded Mesozoic sandstones and mudstones (Gregg 1964) and carry the imprint of Quaternary glaciation in the form of cirques and broad U-shaped valleys. The forest soils are predominantly high country yellow-brown earths with some podzolic soils on terraces (Cutler 1977). *Nothofagus solandri* forests clothe the hillsides up to about 1350 m, above which alpine grasslands and barrens occur. *N.solandri* forests, are often

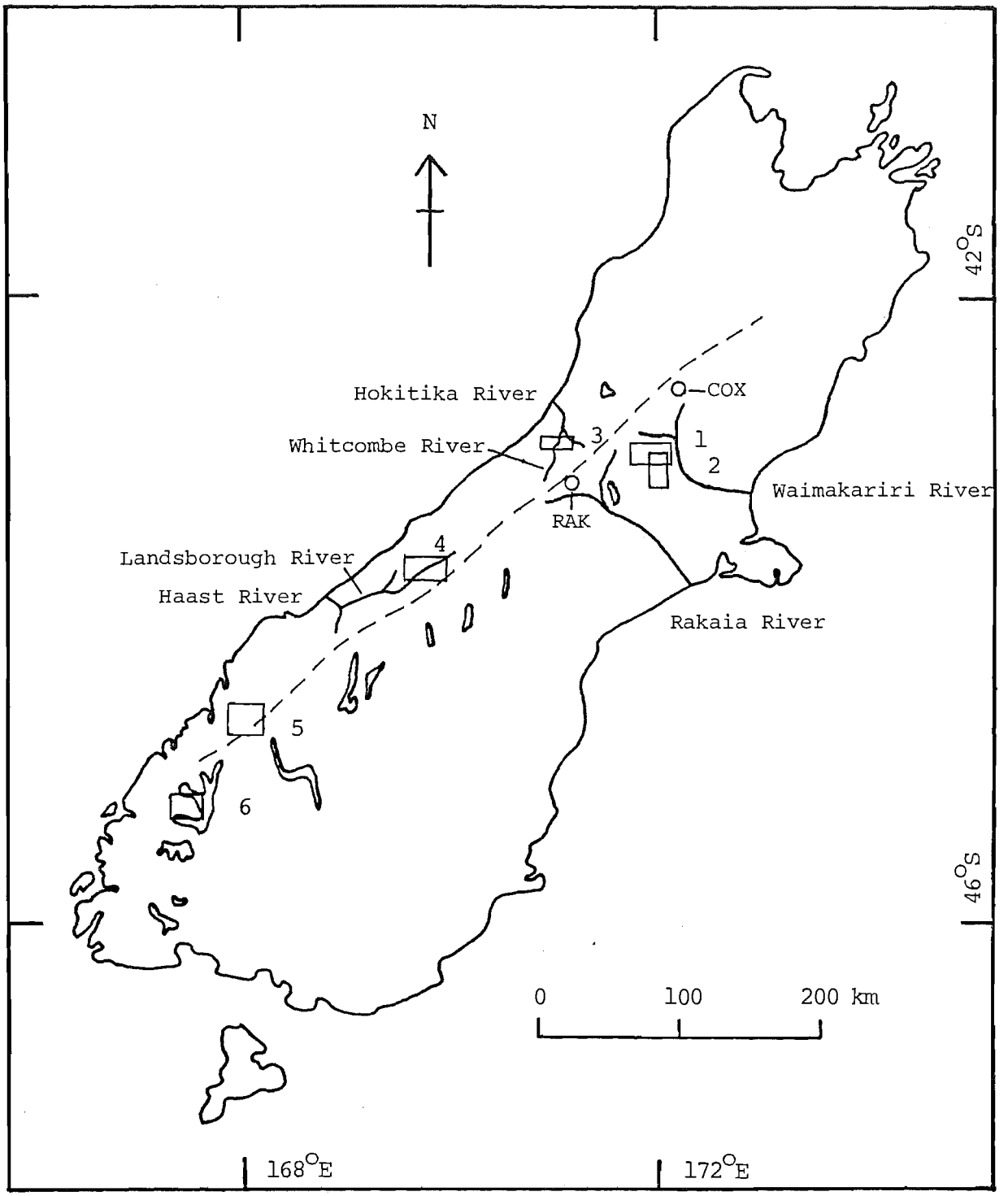


Figure 3.4 Location of the main study areas. 1, Craigieburn Range (Fig. 3.5); 2, Castle Hill and Flock Hill Basins (Fig. 3.7); 3, Whitcombe Valley (Fig. 3.8); 4, Landsborough Valley (Fig. 3.9); 5, Hollyford Valley (Fig. 3.10); 6, Murchison Mountains (Fig. 3.11).

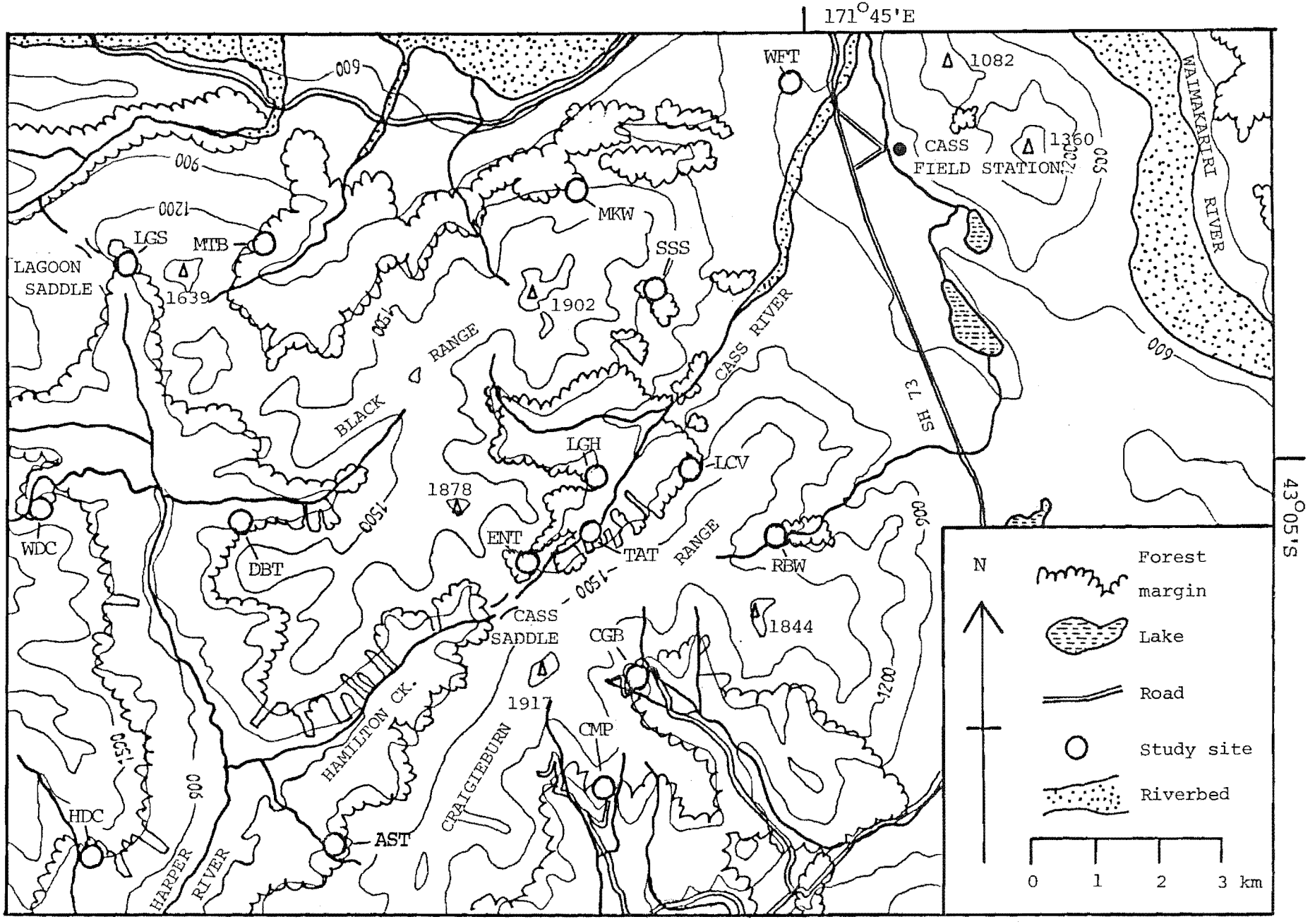


Fig. 3.5 Location of study sites in the Craigieburn Range, Canterbury.

floristically simple with *N.solandri* the only tree species present. At lower altitudes and in wetter regions shrubs and vines often form dense thickets and forbs, ferns and mosses occur on the forest floor. As timberline is approached the forest understorey becomes sparse except where the canopy is open and here the shrubs *Podocarpus nivalis, Phyllocladus alpinus* and *Coprosma* c.f. *pseudocuneata* form thickets. Some alpine species (e.g. in *Chionochloa* and *Celmisia*) extend down into the timberline forests. The forests of the Craigieburn Range have been described in general by Cockayne (1926, 1928), J. Wardle (1970b) and Burrows (1977a), while the timberline ecotone is described in Appendix 2. Avalanches have had a marked influence on the area, locally depressing timberlines and modifying the alpine grasslands (Conway 1977, Burrows et al. 1980).

The Craigieburn Range is the only sampling area for which detailed climatic information is available from a closely adjacent site (Fig. 3.6). The climate of the area has been described by McCracken (1980) and is comparable with the climate of much of the eastern mountain region of Canterbury (Coulter 1973). The weather is dominated by the flow of westerly winds controlled by the passage of anticyclones over the Tasman Sea. Screen temperatures from a station 200 m above timberline (1500 m) in the Broken River Ski Basin ranged from $-18^{\circ}C$ to $+25^{\circ}C$. February is the warmest month with a mean daily temperature of $+9.7^{\circ}C$ while for July, the coldest month, the mean is $-1.4^{\circ}C$. Frosts occur frequently and the average screen-frost-free period is 40 days while a true ground-frost-free period does not exist. Precipitation exceeds 1600 mm per annum and above 1500 m, snowfall accounts for 25% to 40% of this (Prowse 1981). The snowpack usually lasts from May to October but snowfall can occur in any month. Snow persists down to timberline and within the upper forests for much of this period. Wind is a distinctive feature of the weather. Gusts up to 240 kmph have been recorded from the climate station at 1550 m and gusts exceeding 100 kmph have been recorded in all months except February. Because the atmosphere over the Craigieburn Range is often clear, radiation levels are usually higher than at lower altitudes and clear, fine days are common (McCracken 1980).

Twenty-one sites were sampled in the Craigieburn Range and their locations are marked on Fig. 3.5. Of these sites, fourteen are at timberline, six form part of an altitudinal transect of sites on

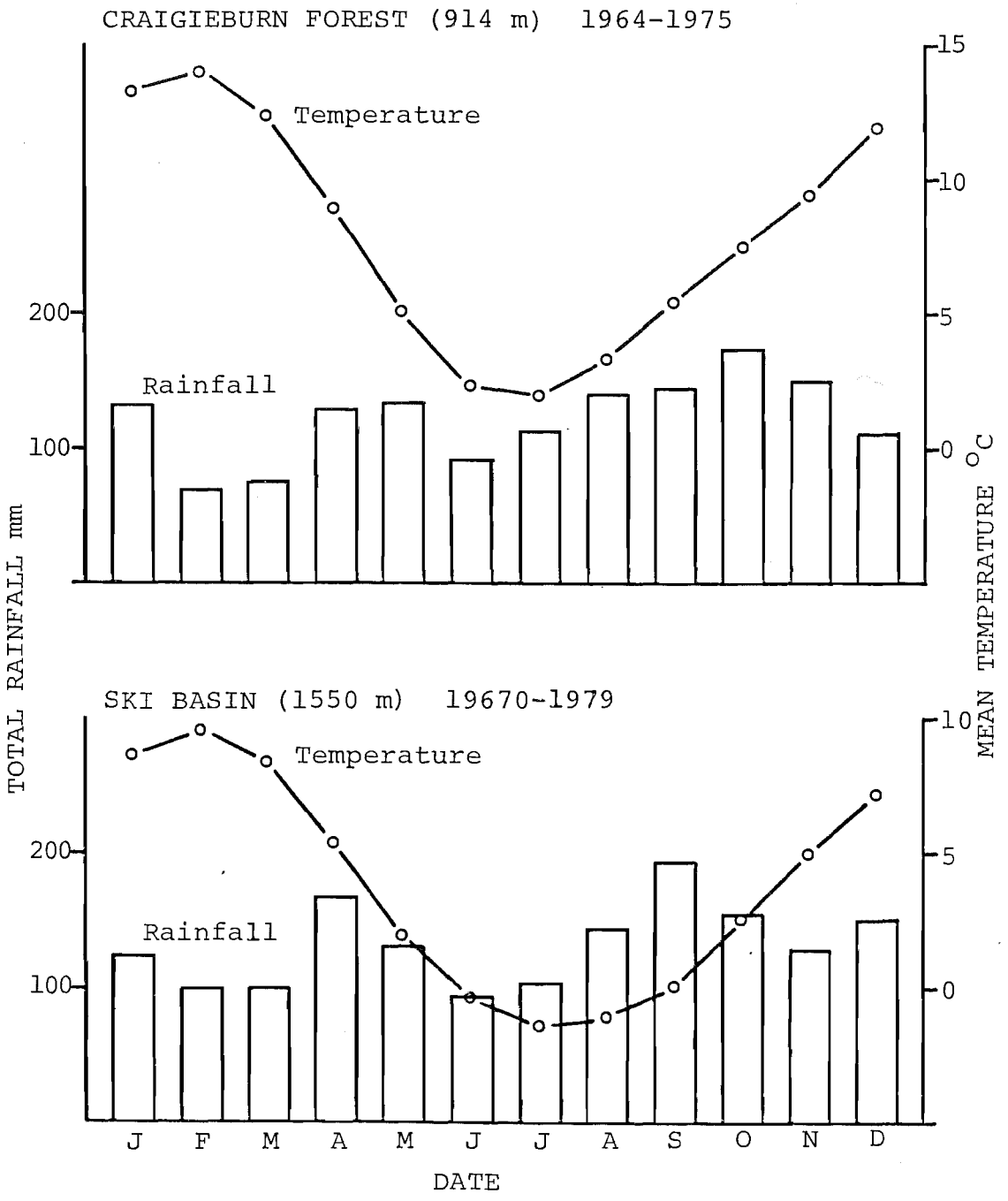


Figure 3.6 Monthly mean temperaure and total rainfall from two sites in the Craigieburn Range. Data from McCracken (1980).

TABLE 3.2 Summary characteristics of sites sampled in the Craigieburn Range.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
AST	NS	1300	SW	35	December 1980
CGB	NS	1250	NE	35	December 1980
CMP	NS	1350	SE	30	December 1980
DBT	NS	1400	NE	30	December 1980
ENT	NS	1250	NE	5	December 1980
HDC	NS	1350	W	30	December 1980
LCV	NS	1350	N	20	February 1981
LGH1	NS	1400	N	30	December 1980
LGH2	NS	1300	E	30	December 1980
LGH3	NS	1200	SE	25	December 1980
LGH4	NS	1100	NE	25	December 1980
LGH5	NS	1000	SE	5	January 1981
LGH6	NS	900	N	30	January 1981
LGH7	NS	800	SE	0	January 1981
LGS	NS	1300	SW	15	January 1981
MKW	NS	1275	NW	30	December 1980
MTB	NS	1300	SE	35	(March 1979 (January 1981
RBW	NS	1350	SE	20	January 1981
SSS	NS	1250	SE	25	January 1981
WDC	NS	1350	NW	30	December 1980
WFT	NS	610	SE	5	February 1980

Note 1: NS, *Nothofagus solandri*

Logos Hill and one site is on the floor of Cass Basin at an altitude of 650 m. The mean altitude of the timberline sites is 1300 m. Seven of the sites have southerly aspects and seven, northerly aspects. All these sites are in tall forest close to timberline. Along the altitudinal transect, sites were located at 100 m altitudinal intervals from timberline at 1400 m to valley floor at 800 m. The sites in the Craigieburn Range cover an area of about 15 km^2 and the most distant sites are about 18 km apart. The site characteristics are summarised in Table 3.2 and detailed descriptions are given in Appendix 4.

3.3.2 Castle Hill and Flock Hill Basins

These two areas, adjacent to the Craigieburn Range (Fig. 3.4), are intermontane depressions surrounded by mountain ranges rising to 2000 m (Fig. 3.7). The floor of Flock Hill Basin is covered by beds of alluvium and some till. Tertiary limestones on the floor of Castle Hill Basin are covered by alluvial deposits. The surrounding mountains are composed of Mesozoic sandstones (Gregg 1964). Flock Hill Basin is partially filled by Lake Pearson (600 m); slightly dissected fans, floodplains and moraines are the main landforms. In Castle Hill Basin considerable stream dissection of the basin floor has resulted in the formation of gorges, scarps and terrace flights.

There are many small forest patches in this area on bluffs, talus slopes and in stream gullies. They are relicts of previously more extensive forest (Burrows 1960). Fire has been important in removing forest (Molloy 1977) and deforested areas are now in modified grassland and shrubland used primarily for pastoral farming. The forest remnants are dominated almost solely by *Nothofagus solandri* and have a very sparse and open understorey with little ground vegetation (equivalent to association D1 of J. Wardle 1970b). The climate of these inland basins has not been described in detail. Rainfall is approximately 913 mm per annum at Castle Hill Station (Fig. 3.7) at an altitude of 741 m a.s.l. and summers can be warm and dry. Heavy winter snowfalls occur to low levels in winter and spring (Burrows 1976a).

Three sites have been sampled previously in this area (Norton 1979, Aston 1982) and the data from these investigations is re-examined in the present study. These sites are forest remnants on bluffs and

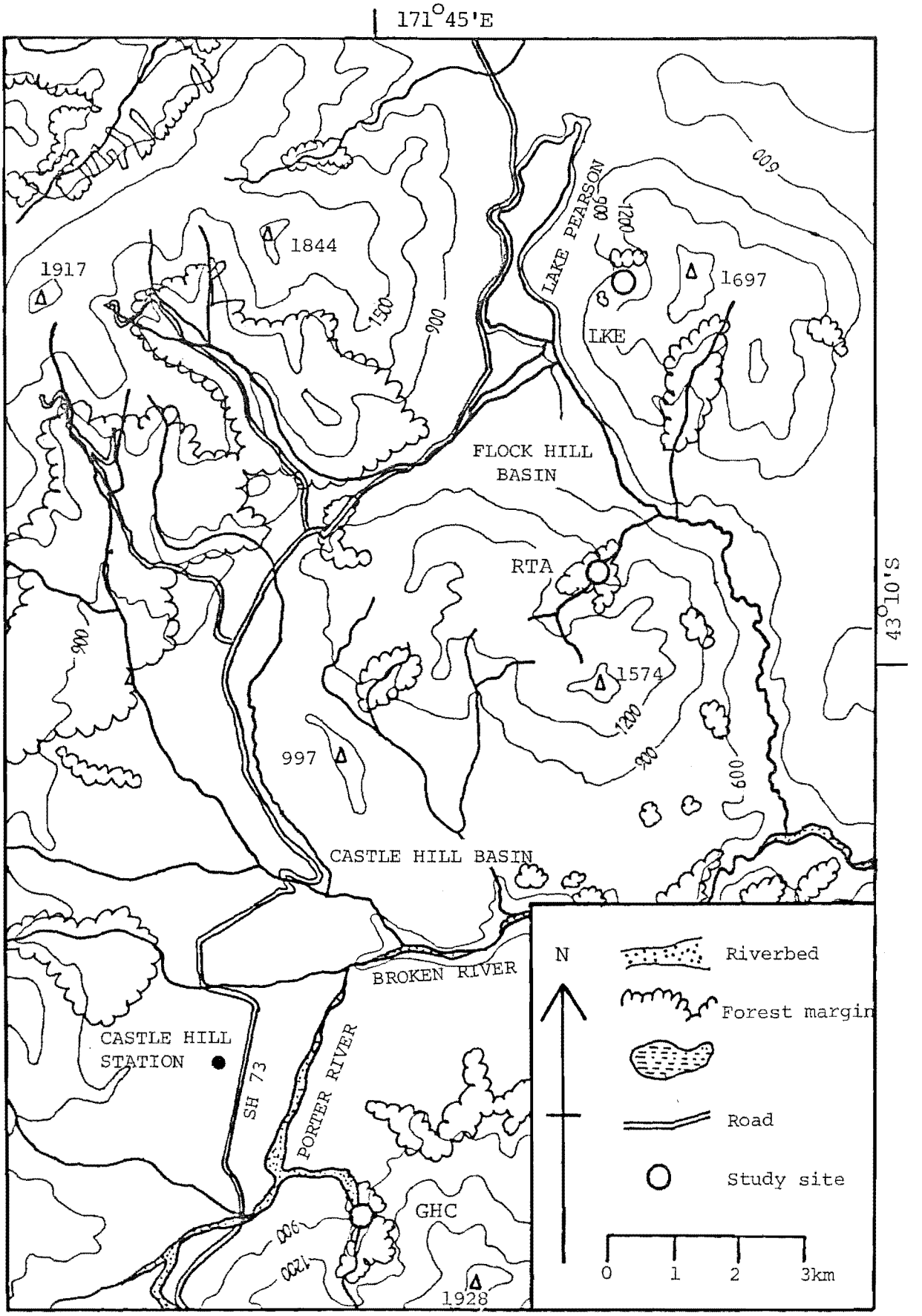


Figure 3.7 Location of study sites in Castle Hill and Flock Hill Basins, Canterbury.

steep talus slopes at low altitude in the basins. Site details are summarised in Table 3.3 and detailed descriptions given in Appendix 4.

TABLE 3.3 Summary characteristics of sites sampled in Castle Hill and Flock Hill Basins.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
GHC	NS	870	NW	30	July 1981
LKP	NS	970	NW	25	April 1979
RTA	NS	950	N	25	July 1981

Note 1: NS, *Nothofagus solandri*

3.3.3 Whitcombe Valley

The Whitcombe River is situated west of the main divide of the Southern Alps and flows northwest from Mount Evans (2638 m) until joining the Hokitika River (Fig. 3.4). The study was undertaken in the Cropp River catchment, a tributary of the Whitcombe River (Fig. 3.8). The Cropp River flows eastwards for a distance of about 8 km from under Mount Beaumont (2143 m) before joining the Whitcombe River. There is continuing rapid tectonic uplift in this area (Hawkes 1981) resulting in steep, rugged topography. Erosion is widespread within and above the forest zone. Steeply-dipping biotite schists with lenses of schistose serpentinite form the dominant rock type (Hawkes 1981). A variety of soils occur depending on topography, age and vegetation. Mature soils are often gleyed.

The climate of the study area is typical of that to the west of the main divide of the South Island (Hessell 1982) and lies in the belt of maximum rainfall, with rainfall of up to 10 000 mm per annum (Griffiths and McSaveney 1983). No long-term temperature records are available, but summer night frosts have been recorded. Strong to galeforce northwesterly winds are frequent and are often accompanied by heavy rain and electrical storms. Cloudiness is common. Snow lies on the tops and extends down into the forest zone during the winter months.

The vegetation of the Cropp River catchment is similar to that described elsewhere for South Westland (James et al. 1973, P. Wardle 1960, 1977). At lower altitudes there are mixed conifer-angiosperm

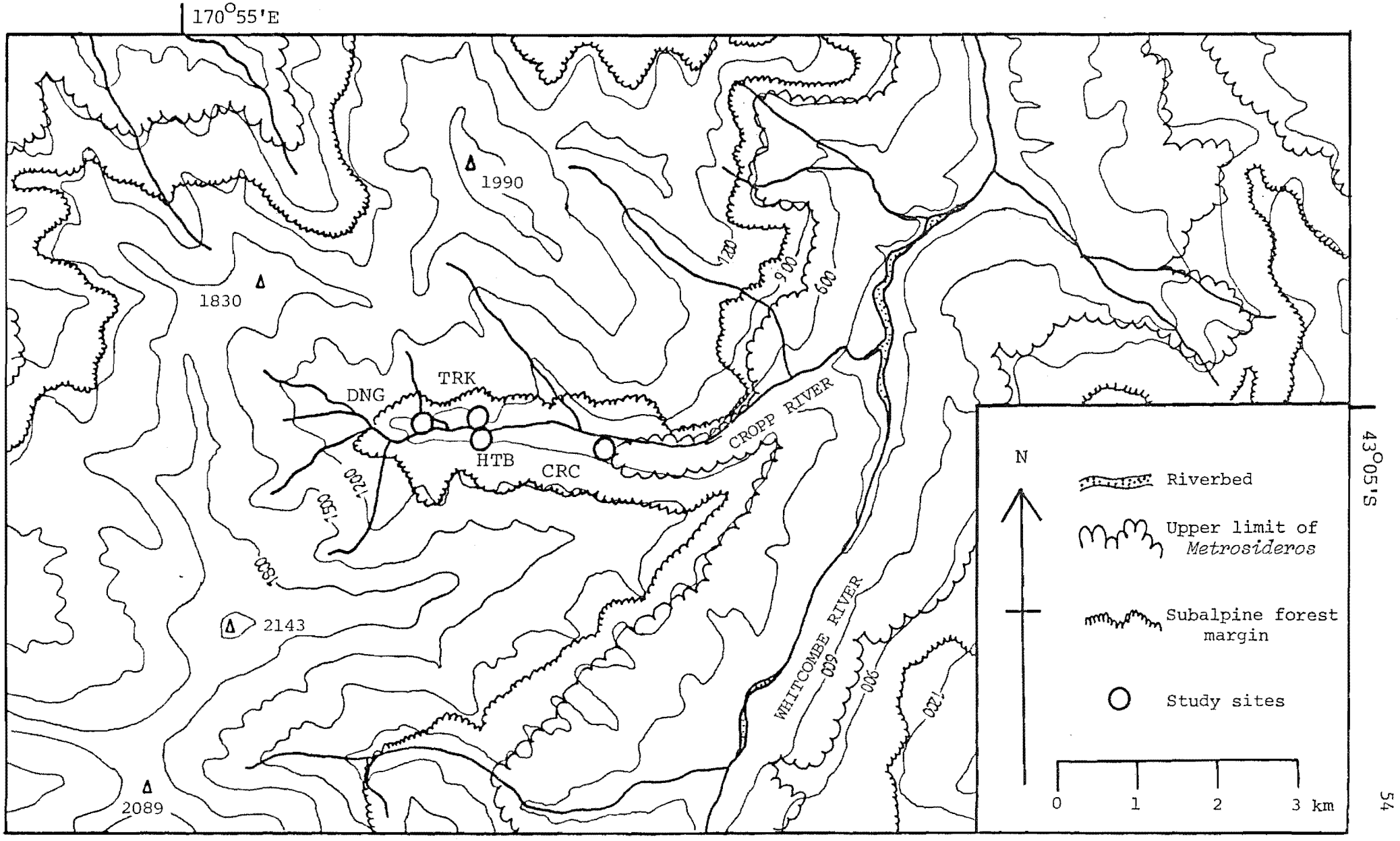


Figure 3.8 Location of study sites in the Whitcombe Valley, Westland.

forests, with *Dacrydium cupressinum, Podocarpus ferrugineus* and *P.hallii* emergent over an angiosperm canopy dominated by *Weinmannia racemosa*. Extensive forests of often even-aged *Metrosideros umbellata* and *W.racemosa*, frequently in association with *P.hallii*, occur on mid altitude slopes. High altitude or subalpine forests are characterised by the presence of *Libocedrus bidwillii*, and occur widely from about 700 m to 1000 m elevation. A low canopy of *Olearia, Senecio, Dracophyllum* and *Archeria* shrubs with emergent *L.bidwillii* trees is typical. This community commonly occurs on well-drained soils and the stands sampled are on such sites. These subalpine forests with *L.bidwillii* belong to the tree-composite forest of Cockayne (1928),the *Olearia* low forest of P. Wardle (1960) and the *Dracophyllum-Olearia* scrub of P. Wardle (1977). They have been described in some detail by these authors. The population dynamics of these forests have been discussed by P. Wardle (1963c, 1978), Veblen and Stewart (1982) and in Appendix 1. With increasing altitude, forest with *Libocedrus* is replaced by subalpine scrub communities, described by P. Wardle (1960). Above the limits of erect woody vegetation there are *Chionochloa* grasslands and alpine barrens.

Four sites were sampled in the Cropp River catchment and their locations are marked on Fig. 3.8. All sites are in subalpine forest and occur at a mean altitude of 900 m. Floristically the four sites are similar, but one (CRC) is 1.5 km from the other three closely located sites. All trees in the stands were sampled as part of a population census (Appendix 1). The site characteristics are summarised in Table 3.4 and detailed site descriptions are given in Appendix 4.

TABLE 3.4 Summary characteristics of sites sampled in the Whitcombe Valley.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
CRC	LB	820	N	15	January 1980
DNG	LB	960	NE	35	January 1980
HTB	LB	930	N	30+	January 1980
TRK	LB	910	SW	30	January 1980

Note 1: LB, *Libocedrus bidwillii*.

3.3.4 Landsborough Valley

The Landsborough Valley is located in South Westland (Fig. 3.4) and is oriented parallel to the main divide of the Southern Alps for 60 km until the Landsborough River joins the Haast River, 40 km from the coast (Fig. 3.4). Above the junction with the Haast River, the Landsborough Valley lies between two heavily glaciated mountain ranges with peaks over 2600 m; the Main Divide to the east and the Hooker Range to the west (Fig. 3.9). The mountains are composed of strongly schistose and finely foliated quartzo-feldspathic schist of Mesozoic age (Gair 1967). The soils under *Nothofagus menziesii* forest are commonly podzolised yellow-brown earths (New Zealand Soil Bureau 1968); organic soils occur near timberline. The climate of the area has been described by P. Wardle (1979a) and Hessell (1982). As elsewhere in Westland, climate is dominated by the passage of anticyclones over the Tasman Sea and is associated with westerly airflow. Rainfall is probably in excess of 6000 mm per annum but is likely to vary considerably within the valley, particularly from east to west. Snow lies above and down to timberline from about June to September or October.

The vegetation of the upper Landsborough has been described by P. Wardle (1977, 1979a, 1980a) in conjunction with that of Westland National Park immediately to the north and is similar to that found elsewhere in South Westland (J. Wardle et al. 1973, Mark 1977). The sole tree species in the forests of the upper Landsborough is *Nothofagus menziesii* at approximately the northern most distribution of its range in South Westland (P. Wardle 1980a). Timberline occurs between 1150 m and 1220 m but drops at the head of the valley (Fettes Glacier area) where *N.menziesii* appears to be actively expanding its range. At lower altitudes, trees are tall (over 20 m) but nearer timberline they rarely exceed 10 m and are often gnarled. Below the closed *N.menziesii* canopy, a varied and often dense scrub layer occurs and includes *Pseudowintera colorata, Pseudopanax simplex, Griselinia littoralis, Myrsine divaricata, Coprosma* spp. and nearer timberline, *Phyllocladus alpinus, Archeria traversii* and *Dracophyllum* spp. A thick cover of ferns, mosses and herbaceous plants occurs on the forest floor. Avalanche tracks are conspicuous in the forests of the upper valley and above timberline extensive alpine grasslands and barrens occur.

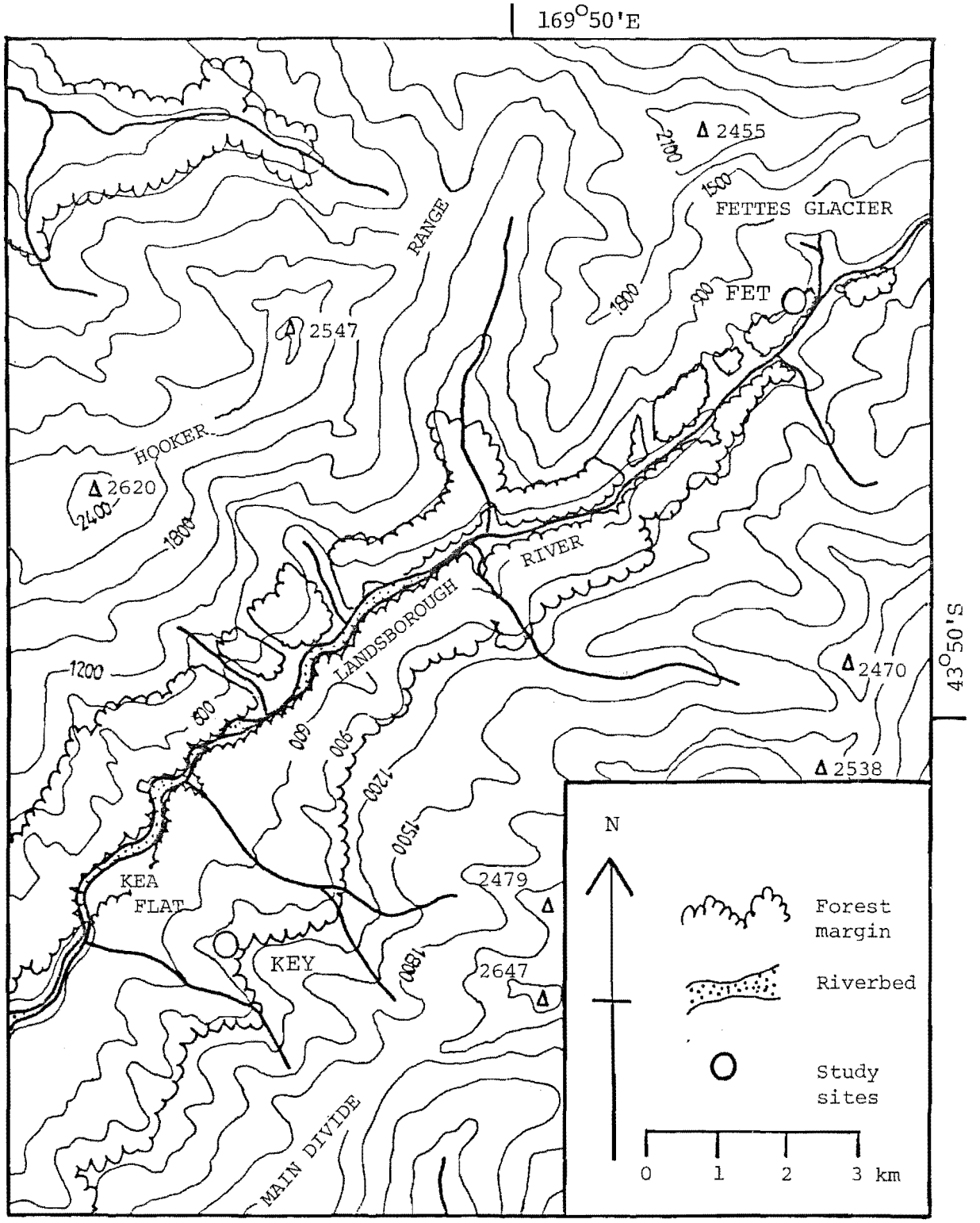


Figure 3.9 Location of study sites in the Landsborough Valley, South Westland. Glaciers and permanent snowfields are not marked.

Poor weather restricted sampling to only one site (KEA), situated near timberline in the upper valley. Exploratory corings were also taken from trees elsewhere in the upper valley (Table 3.5). A detailed description of the KEA site is given in Appendix 4.

TABLE 3.5 Summary characteristics of sites sampled in the Landsborough Valley.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
KEA	NM	1150	NW	15	February 1982
FET	NM	800	SE	10	February 1982

Note 1: NM, *Nothofagus menziesii*

3.3.5 Hollyford Valley

The Hollyford River drains the southern and eastern flanks of the Darran Mountains in north Fiordland (Fig. 3.4 and 3.10). The Hollyford Valley floor is narrow and flat with steep valley sides. To the west, glacier-cut U-shaped valleys and glaciated mountain peaks of the Darran Range rise to over 2500 m. The Humboldt Range in the east is lower (under 2000 m) and carries little permanent snow and ice. The geology of the area is complex with Palaeozoic schistose sandstones of the Humboldt Range faulted against Palaeozoic rocks of the Darran Mountains which are massive, weakly gneissose diorites and granodiorites (Wood 1962).

The climate of the area has not been described in detail. Rainfall exceeds 7000 mm per annum in the upper Hollyford Valley but drops to 4000-5000 mm per annum further east (Mark and Sanderson 1962); snowfalls occur regularly in winter. No temperature data are available.

The vegetation of Fiordland has been described by Cockayne (1928) and Holloway (1954) and the forests of the Hollyford Valley by Mark and Sanderson (1962). Forests in the adjacent valleys of Mount Aspiring National Park are similar (Mark 1977). The floor and lower slopes of the Hollyford Valley are occupied by beech-podocarp-kamahi forest with *Nothofagus fusca, N.menziesii, Dacrydium cupressinum, Podocarpus ferrugineus* and *P.hallii* forming an open canopy above *Weinmannia racemosa*.

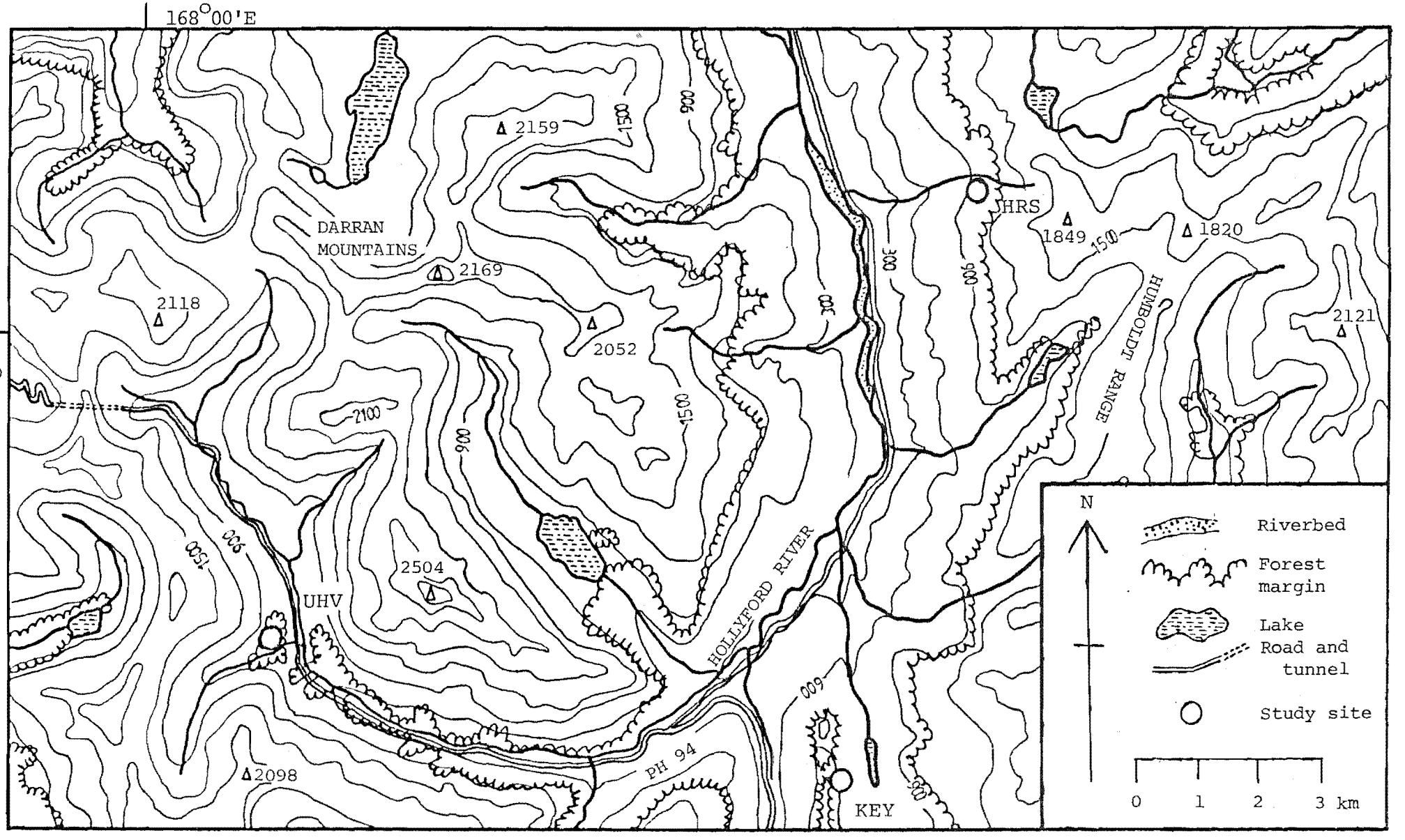


Figure 3.10 Location of study sites in the Hollyford Valley, Fiordland. Glaciers and permanent snowfields not marked.

The upper forests are pure *N.menziesii* and form timberline at approximately 1000 m to 1050 m. These upper forests lack the well defined small tree layer present at lower altitudes but have a dense scrub layer which can include *Olearia ilicifolia, Archeria traversii, Senecio benettii, Pseudopanax colensoi, Phyllocladus alpinus* and *Coprosma* spp. Above timberline, extensive alpine grasslands occur. Many of the forests have been modified by avalanche, especially in the Upper Hollyford Valley (Conway 1977, Fitzharris and Owens 1980) and here, full forest cover is restricted to avalanche-free sites. The forest soils are predominantly upland and high country podzolised yellow-brown earths and podzols (New Zealand Soil Bureau 1968).

Three sites were sampled in the Hollyford Valley; their locations are marked on Fig. 3.10. All sites are in pure *Nothofagus menziesii* forest close to timberline. The sites are floristically similar. Site characteristics are summarised in Table 3.6 and described in detail in Appendix 4.

TABLE 3.6 Summary characteristics of sites sampled in the Hollyford Valley.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
HRS	NM	1050	W	20	November 1981
KEY	NM	1000	E	15	November 1981
UHV	NM	950	S	10	November 1981

Note 1: NM, *Nothofagus menziesii*

3.3.6 Murchison Mountains

The Murchison Mountains lie between the Middle and South Fiords of Lake Te Anau (Fig. 3.4 and 3.11). The area is a deeply dissected upland rising to 1800 m in places. The landscape shows the imprint of Quaternary ice advances, with glacier-eroded valleys, fiords, cirques and steep mountain peaks, but without permanent snow and ice. The eastern side directly adjacent to Lake Te Anau is more gentle with low angle slopes down to lake level. The geology is complex with medium-grained weakly foliated microcline granites of Palaeozoic age in the east and hornblende-plagioclase schists and paragneiss in the west (Wood 1962). In some places (e.g. at the eastern end of Takahe Valley) the granites are overlain by Tertiary limestones.

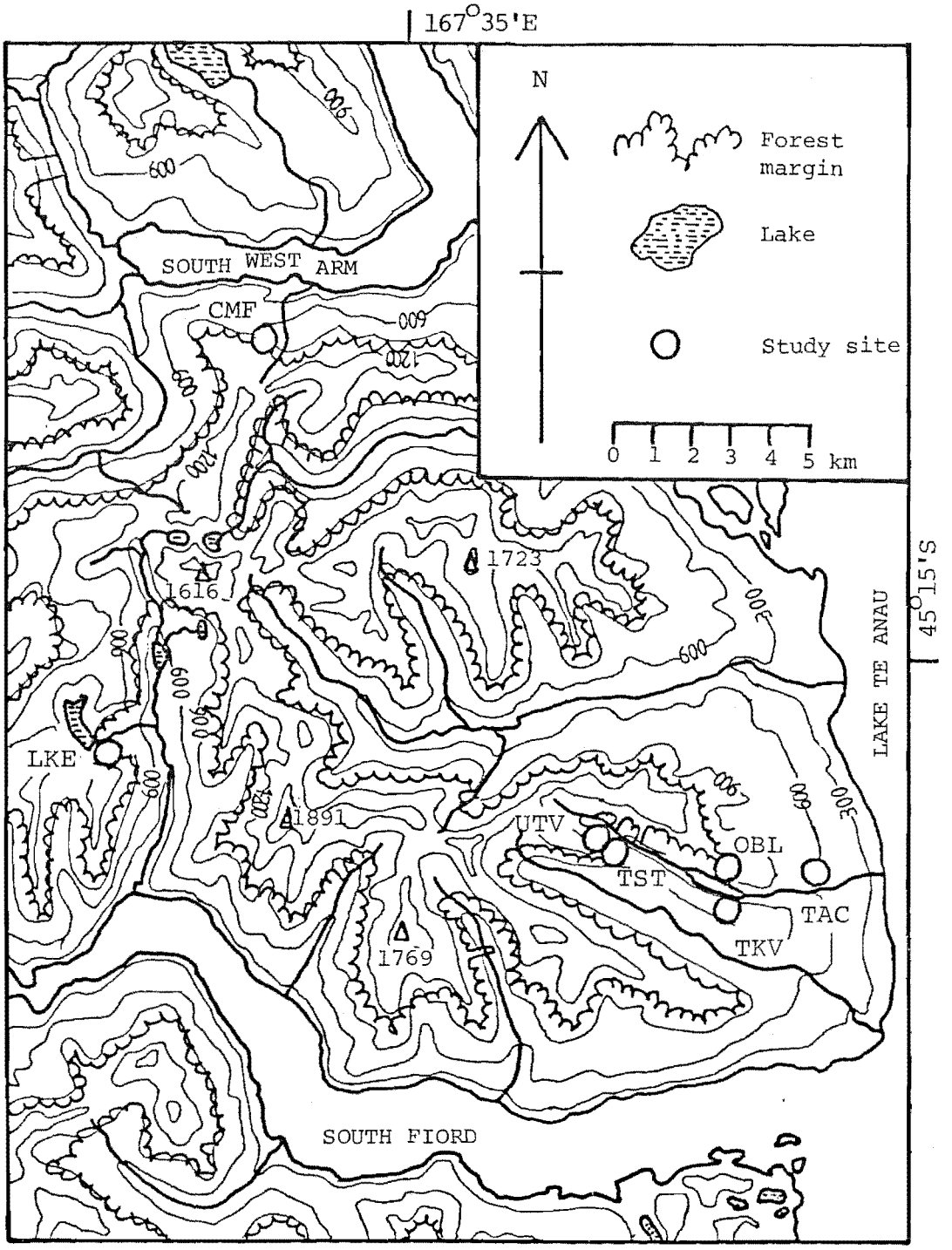


Figure 3.11 Location of study sites in the Murchison Mountains, Fiordland.

TABLE 3.7 Summary characteristics of sites sampled in the Murchison Mountains.

Code	Species[1]	Altitude (m)	Aspect	Slope (°)	Sampling date
CMF	NM	1000	N	30	January 1981
LKE	NM	950	NE	0	November 1981
OBL	NM	1000	S	20	(February 1981 (November 1981
TKV	NS	1100	N	20	February 1981
TST	NS	1000	NE	15	February 1981
UTV	NM	1000	NE	15	February 1981

Note 1: NM, *Nothofagus menziesii;* NS, *N.solandri*

General observations on the climate have been made by Robertson (1951) and Hessell (1982) and recent detailed recordings have been made in the Murchison Mountains by the Wildlife Service (R.B. Lavers pers. comm. 1982, Fig. 3.12). Northwesterly winds are prevalent during summer and southeasterlies in winter. Rainfall decreases sharply from west to east. The rainfall average (for 1976 to 1980) at Milford Sound, Lake Eyles, Takahe Valley and Te Anau was 6231 mm, 4541 mm, 2486 mm and 1112 mm respectively. Rainfall is greater in summer. Temperature from a station at 890 m on the floor of Takahe Valley ranged from -15.0°C to +27.0°C for the period 1973 to 1981. January and February are the warmest months with a mean daily temperature of 10.6°C while July is the coldest month with a mean daily temperature of -0.7°C. Allowing for altitudinal and site differences, these values are comparable to those obtained in the Craigieburn Range by McCracken (1980). Snow persists down to timberline from June to September. The forests of the area immediately to the northwest were described by Holloway (1951) while J. Wardle et al. (1971) discussed forests occurring between Lake Te Anau, the western coast and Milford Sound. J. Wardle (1978) discussed the forests of the Murchison Mountains and recognised ten forest types. On the lower and mid slopes tall *Nothofagus menzeisii* forest, often in association with *N.fusca, N.solandri* (in the east) and *Weinmannia racemosa,* is common. In Takahe Valley and the Point Burn, mixed *N.menziesii-N.solandri* occurs above this and *N.solandri* forms timberline at about 1000 m to 1100 m. Elsewhere, pure *N.menziesii* forests occur at timberline. Both

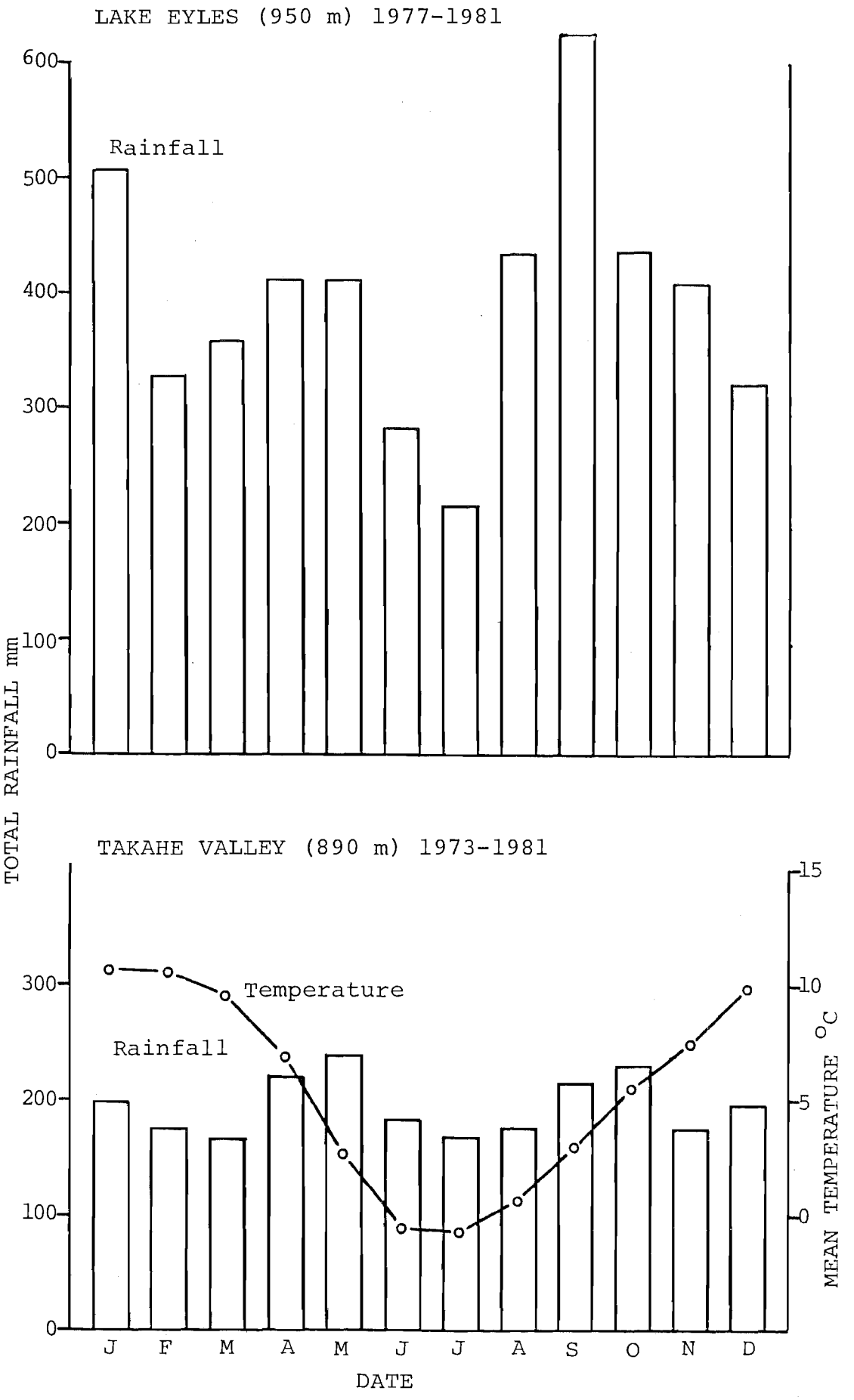


Figure 3.12 Monthly mean temperature and total rainfall from two sites in the Murchison Mountains. Data from the New Zealand Wildlife Service.

N.solandri and *N.menziesii* timberline forests have a dense scrubby understorey of *Archeria traversii, Myrsine divaricata, Pseudopanax simplex* and *Coprosma* spp. Ferns, mosses and herbaceous plants are common on the forest floor.

Six sites were sampled in the Murchison Mountains (Fig. 3.11, Table 3.7). Two (CMF, LKE) are in pure *Nothofagus menziesii* forest near timberline while the remaining sites (OBL, TKV, TST, UTV) in Takahe Valley are in mixed *N.menziesii-N.solandri* forests. Detailed site descriptions are given in Appendix 4.

3.3.7 Miscellaneous sites

Two exploratory samples were made to the north and south of the Craigieburn Range (Fig. 3.4). The northerly sample was located near timberline in the upper Poulter Valley and the southern sample near timberline in the Rakaia Valley. Both sites are in pure *Nothofagus solandri* forest. Three buried *N.solandri* logs were recovered from alluvial deposits at the base of an avalanche track (950 m) in the Cass Valley (Fig. 3.5). Cores were also taken from both *N.solandri* and *N.menziesii* trees at 600 m between Lake Te Anau and Takahe Valley (Fig. 3.11). Details of these sites are also given in Appendix 4.

During 1977 and 1978, members of the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, visited New Zealand and sampled widely a variety of species from a variety of sites (Dunwiddie 1978, 1979). Chronologies developed from several of these sites are used for comparison with those of this study in Part II of this thesis and are climatically analysed in Part III. Details of the sites sampled and the chronology statistics are presented by LaMarche et al. (1979c).

CHAPTER FOUR

DENDROCHRONOLOGICAL METHODS

4.1 FIELD PROCEDURE

Field sampling was undertaken during the summers of 1979-1980, 1980-1981 and 1981-1982. Details of the species used and sites sampled have been given in Chapter 3. Two cores were usually extracted from each of 10 to 20 trees at each site, although the actual number of trees sampled and cores taken per tree varied (see Appendix 4). Criteria for tree selection were that they were of good form (not gnarled), large size (and hence likely to be old) and had good circuit uniformity (similar ring width patterns on all radii). In the mesic forests of New Zealand, the very old, gnarled trees that have proved of most value in western North America are of least use because growth in these trees is irregular with local bands of absent rings. Many also have rotten heart wood. Instead, large, straight-boled trees have yielded the best information (Dunwiddie 1979, Norton 1979) and it was trees of this form that were sampled in the present study. These trees also have the best circuit uniformity.

Cores were extracted approximately 1 m above the ground using a Swedish increment borer. Increment borers are precision tools and regular cleaning and sharpening was essential to obtain clean, straight cores. Coring procedures are described further by Stokes and Smiley (1968) and Burrows and Burrows (1976). Cores were extracted from opposite sides of the tree and, where possible, across the slope. An attempt was made to reach the centre of each tree but this was not always achieved, especially for *Libocedrus bidwillii* whose centres were commonly rotten. After core extraction, the borer holes were plugged with vaseline to prevent insect or fungal infection. The fragile increment cores were stored in labelled drinking straws for safety. At some sites trees were felled and discs taken at 1 m intervals up the bole to assess vertical uniformity of ring width patterns.

At each site, notes were made on site factors (slope, aspect, soils, vegetation etc.) and other relevant features (e.g. evidence of

windbreak and landslide) that might help interpret the results. Information was also recorded on the tree growth form and position of cores. Diameter at coring height was measured for all sampled trees. An example sheet of the site information recorded is given in Appendix 6 and tree information in Appendix 6.

4.2 LABORATORY PROCEDURE

4.2.1 Core and disc preparation

The cores were air-dried and glued into grooved wooden blocks with the transverse surface upwards. This provided a strong permanent mount. Oven-drying causes breakage and severe twisting. Correct core orientation is essential if the growth rings are to be seen clearly. The cores were therefore always mounted and labelled so that the most recent ring (and the bark) was on the right-hand side. The discs were also air-dried and chainsaw marks removed using an electric plane.

A good surface for counting and measuring the growth rings was obtained by sanding the cores and discs with successively finer grades of sandpaper. Sandpaper grades used were 40, 70, 150, 270 and 360 (or 400) and the sanding was done using an electric orbital sander. Belt sanders were not used as they leave scour marks in the wood. The finish obtained was such that the cellular detail of the rings could be seen clearly. Before examination under the microscope, cores and discs were rubbed with tissue paper to remove dust and to produce a very fine polish. With all three species examined in this study, staining the wood to examine the growth rings was not necessary.

4.2.2 Crossdating

"Crossdating is the most important principle of dendrochronology" (Fritts 1976, p.20). Crossdating involves the matching of similar ring width patterns between different trees and is possible because the same or similar environmental conditions (usually climate) limit growth of a large number of trees in a similar way. As climatic conditions vary from year to year, so too do ring widths. It is the matching of these variable patterns of ring widths that ensures the accurate dating of all tree-ring material. Crossdating is therefore a form of experimental control as it provides an absolute time base for all tree-ring sequences. The ability to crossdate is confirmation

of the assumption made in Chapter 3, that some environmental (probably climatic) factor is limiting tree growth at a particular site.

In some years, climatic conditions are such that tree growth is severely reduced. At these times little radial growth occurs and may be localised to certain radii around the stem or in some instances may not occur at all. These growth rings are said to be "partial", "locally absent" or "missing" along certain radii (Fritts 1976). Changes in cell structure can occur during a particular growing season and give rise to bands of narrow cells that resemble latewood and are known as false rings. False rings and locally absent rings are discussed further in Chapter 5.

The occurrence of locally absent rings and false rings places tree-ring sequences out of chronological order and unless occurring synchronously between many trees, prevent crossdating. However, these anomalous rings are easily recognised as on one side of the anomaly the ring width pattern will match with that of other trees, but on the other side, they will not be directly comparable. When these anomalous rings are recognised and taken into account, the ring width series from several trees will match for their entire lengths (Fig. 4.1). If there are a large number of anomalous rings, or for other reasons the ring width series will not match, then the sample is not used for further analysis as its absolute dating is uncertain.

Crossdating can be undertaken in several ways. Skeleton plots are used widely for dating tree-ring series (Stokes and Smiley 1968). A strip of graph paper is labelled with the specimen number and each vertical line on the graph paper corresponds to one ring. In skeleton plotting the narrow rings are the ones primarily being compared, so a line is marked on the graph paper for each narrow ring encountered. By convention, the most recent ring is always placed on the right-hand side. The decision on the narrowness of the ring is based on the comparison of each ring with its nearest neighbours. The narrower the ring, then the longer the line. Average and wide rings are not marked. When all the tree-ring series from a site have been skeleton plotted, they are compared against each other and the plots placed so that similar ring width patterns line up (Fig. 4.2). Anomalous rings can be identified in this way and the plots adjusted accordingly.

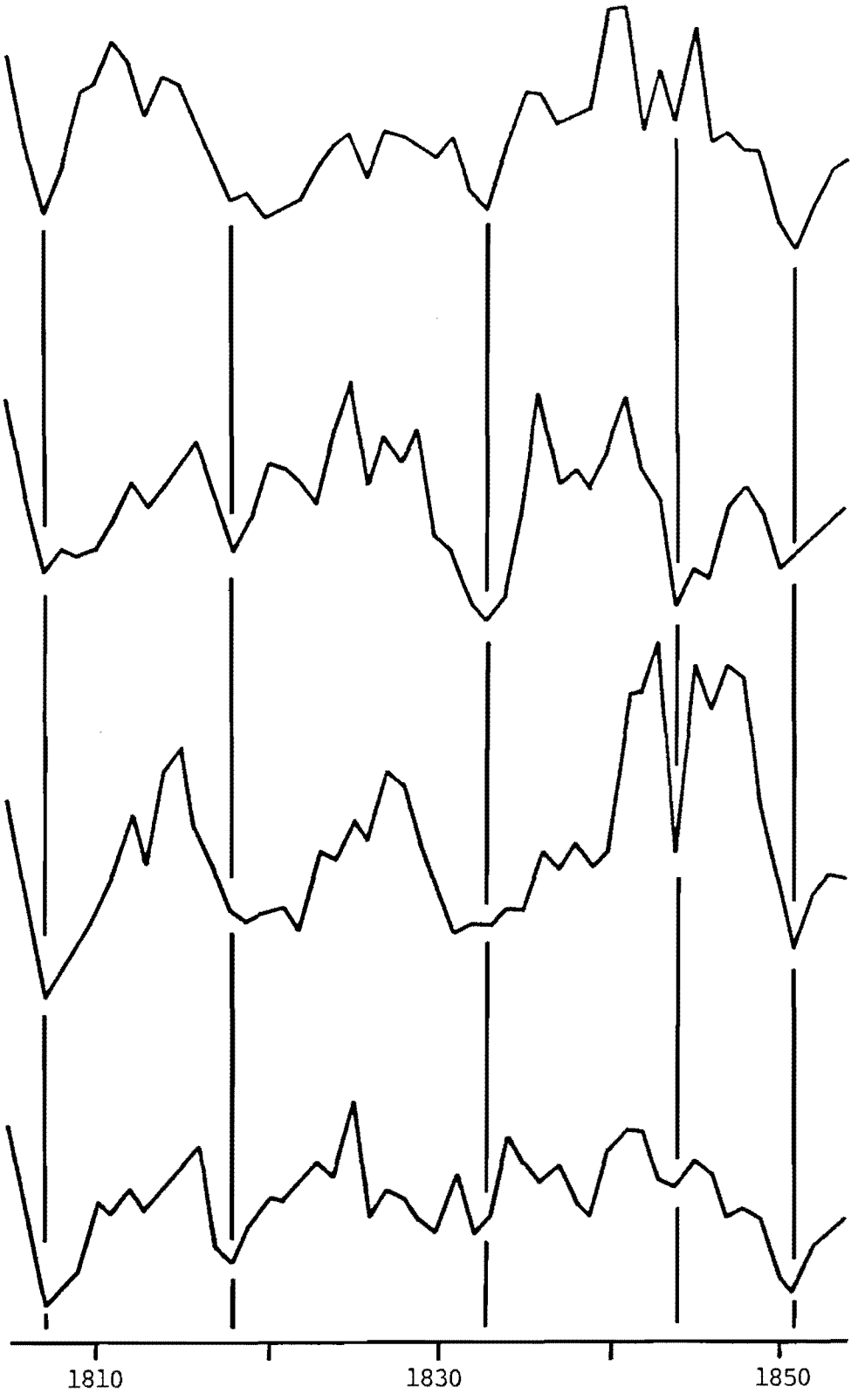


Figure 4.1 Crossdating between 4 trees at the CRC601 site during the period 1805-1855 A.D, Distinctive narrow rings occurred in 1807-1809, 1818, 1833, 1844 and 1851 A.D. (c.f. Fig. 4.2).

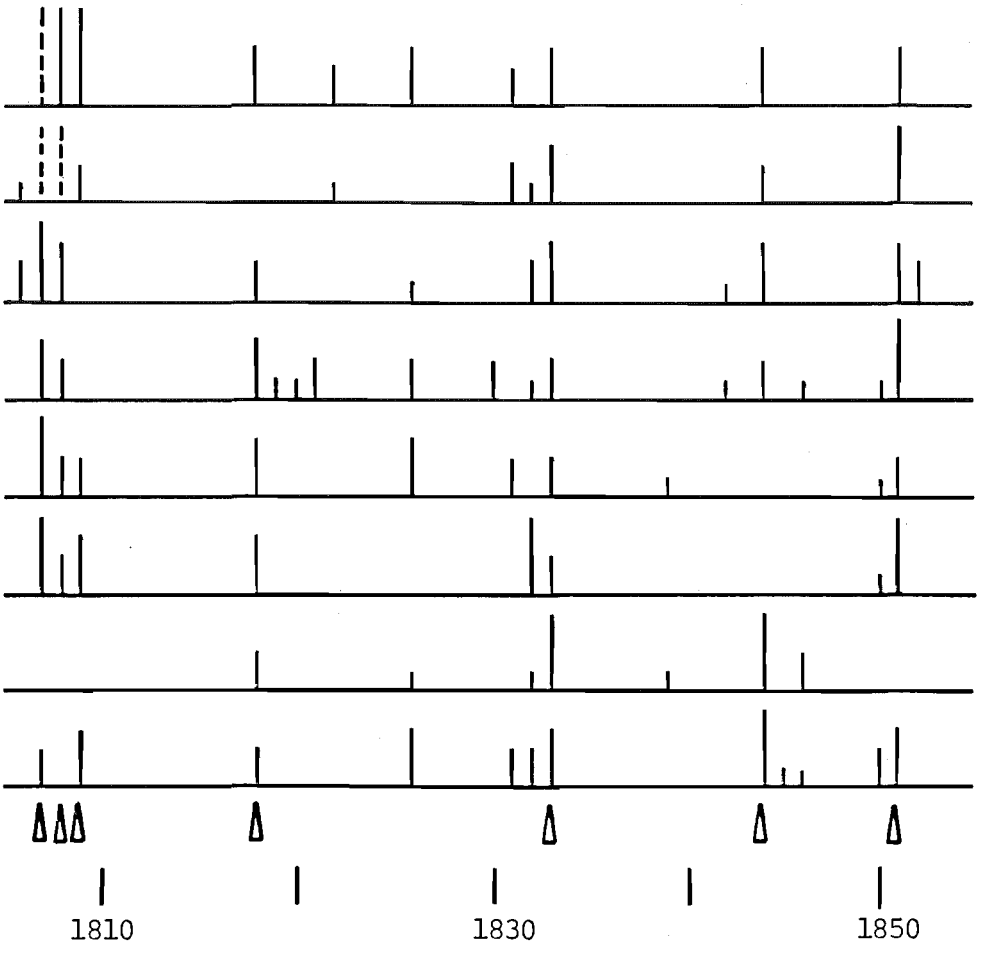


Figure 4.2 Skeleton plots for 8 radii from 4 trees at the CRC601 site during the period 1805-1855 A.D. The longer the line the narrower the ring. Absent rings are indicated by a dashed line. Distinctive narrow rings occurred in 1807, 1808, 1809, 1818, 1833, 1844, and 1851 A.D. (c.f. Fig. 4.1).

Skeleton plotting can be undertaken manually (the more common method) or using a recently developed computer program (Cropper 1979). In this program each tree-ring series is standardised using a low-pass filtered curve fit and small rings are identified using a five year moving mean and a critical level of 0.5 standard deviations from the mean. Narrow rings lie beyond this critical level. The derived skeleton plots are then compared visually. This method makes the identification of narrow rings more objective.

The visual matching of tree-ring series (using skeleton plots) is, to some degree, subjective and statistical techniques have been developed for checking visual matches. Huber and Giertz (1970) developed a method involving the calculation of the percentage parallel variation between two tree-ring series. This measures the number of years when two tree-ring series show similar increases or decreases in ring width. With computers it is possible to slide one curve past another, in one year increments, and calculate the per cent agreement at each point of overlap. The expected agreement of two random series is 50%. All mis-matches should be distributed within three standard deviations of the mean and any value occurring outside these limits is highly significant. Carter (1971) used this method to compare North Island *Nothofagus solandri* tree-ring series. This method has been computerised by Eckstein and Bauch (1969).

A drawback of the percentage agreement method is that it is non-parametric; while calculating the similarities of two ring width series, it does not take into account the magnitudes of year to year change in ring width. Significant crossdating is only demonstrated by the percentage agreement method when there is a long overlap between the two chronologies and the agreement is better than 60 per cent. A direct parametric correlation method, developed by Baillie and Pilcher (1973), measures the degree of correlation between two tree-ring series and expresses the probability of the match using the Students *t* statistic. The method was developed for matching ring width patterns between sequences of unknown relative age and slides the series past each other calculating the probability of the successive matches not occurring by chance. The method assumes that unidentified anomalous rings are not present and in *Quercus*, the genus this method was developed for, this is often true (Baillie 1982). However, with other species including those investigated in this study this assumption is not valid.

The use of correlation coefficients for crossdating has been refined further by Wendland (1975) who has developed a computer program to screen tree-ring series and identify periods of poor correlation. Such periods usually prove, on visual examination, to be the result of false or missing rings and when these are taken into account good correlations are obtained.

Although ring width series can be crossdated using computer techniques, all matches must still be inspected visually before being accepted as true. Because of this, and also because of the large number of absent rings present in some sequences examined here, it was decided not to use computer-based crossdating methods and all crossdating was done visually. Initially several radii with relatively wide and clear growth rings were examined at 10 x and 20 x magnification under an Olympus binocular microscope and distinctive signature rings and ring patterns identified. Signature rings are usually narrow and signature patterns are short sections of distinctive narrow and wide rings. Using these patterns it was possible to match in other radii. Discs were found useful for crossdating initially as it was possible to follow rings completely around the tree but with experience and familiarisation with the ring characteristics of the three species examined, good crossdating could be achieved quickly using cores. At any given site, the radius with the most rings present between given signature rings was assumed to have a complete sequence of rings. Because of the large number of trees and sites investigated for each species and the high degree of crossdating between sites, it was considered unlikely that a particular ring was absent from all the trees examined. Ring width series either do or do not crossdate and thus those series that could not be crossdated were discarded.

4.2.3 Measuring

The crossdated ring width series were measured on an Addo electronic growth ring measuring machine at the School of Forestry (University of Canterbury). Ring widths were measured from the latewood-earlywood boundary, in millimetres to two decimal places, using a Beck-Cassel binocular microscope with crosshairs and a mechanical stage. The ring width was measured electronically as the distance travelled by the stage. Because the growing season in the Southern Hemisphere spans two calendar years, the convention used has been to date a growth ring by the year in which growth started.

Thus, a growth ring that was laid down over the 1980-1981 season is referred to as the 1980 growth ring. The ring width measurements were automatically printed out by the measuring machine and then manually transferred onto computer cards for subsequent analysis on the Burroughs B6900 computer. To check the accuracy of tree-ring measurements, one ring width series was measured twice by myself and independently by two colleagues.

Some measurements were made on the computer compatible full range measuring machine linked to an Apple II plus computer at the Department of Botany, University of Auckland.

4.3 STATISTICAL ANALYSIS

4.3.1 Introduction

In this section the statistical techniques used in chronology development and analysis are discussed. Three computer programs (RWLIST, INDEX and SUMAC) developed at the Laboratory of Tree-Ring Research (University of Arizona) were used and a fourth program (FILTER) was developed during the present study. Many of the techniques used in this study were applied manually in the early days of tree-ring research (e.g. Douglass 1928). Increased sample sizes and more rigorous data evaluation in the 1960's resulted in the development of comprehensive computerised procedures for chronology development and analysis (Fritts 1963, Fritts et al. 1969, Fritts 1976). In the late 1970's, major changes were made to these programs (Graybill 1979a, 1979b, 1982) and these considerably revised programs are used here.

The main aim of the statistical analysis is to develop chronologies that maximise the macroclimatic signal present in the individual tree-ring series and to minimise non-climatic variance. Four different kinds of signal affect tree-rings (Graybill 1982) and can be expressed as,

$$R(t) = C + B + D + E$$

where $R(t)$ is the measured ring width in year t, C is the macroclimate signal common to all trees, B is the age-dependent biological growth trend, D is the tree disturbance signal and includes effects unique to one tree (e.g. competitive suppression) or to many trees (e.g. snow

break, insect attack etc.), and E is the random growth signal unique to each tree-ring sequence. In order to maximise the climatic signal (C), it is necessary to remove or reduce the other variable signals. The computer programs discussed in the rest of this chapter are designed to remove much of this non-climatic variance. For comparison, a chronology, developed using random numbers, was also analysed.

4.3.2 Data inspection

The first program, RWLIST, checks the input ring width measurements for preparation errors (e.g. reversed decades) and lists the data for proof reading. A limited number of descriptive statistics commonly used to characterise tree-ring series are also calculated. Only two or these, mean ring width and mean sensitivity, are of interest here as the others are only used in special cases not relevant to this study (e.g. when the raw data is not standardised, LaMarche 1974a). Mean sensitivity is a statistic designed specifically for tree-ring analysis and measures the relative difference in ring width from one year to the next. The average mean sensitivity (ms_x) for a series is calculated as,

$$ms_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1}-x_t)}{x_{t+1}+x_t} \right|$$

where x_t is each ring width and n the length of the tree-ring sequence (Fritts 1976). Mean sensitivity values range from zero when there is no difference from one ring width to the next, to two when a zero value occurs next to a non-zero value. Thus a sensitive tree-ring series is one with considerable year to year variation in ring width. Mean ring width and mean sensitivity values give an idea of the sensitivity of a tree to climate. Fast growing trees, with relatively large mean ring widths and low mean sensitivity values are likely to have been least limited by climate and hence are of limited value for dendro-climatic study. Inspection of these statistics can be used to identify specimens with exceptionally different values which may warrant removal from the data set before subsequent analysis.

The RWLIST program plots 20 year ring width averages, shifted by ten year increments, for each specimen (Fig. 4.3). These plots show long term trends in tree growth and allow detection of the growth

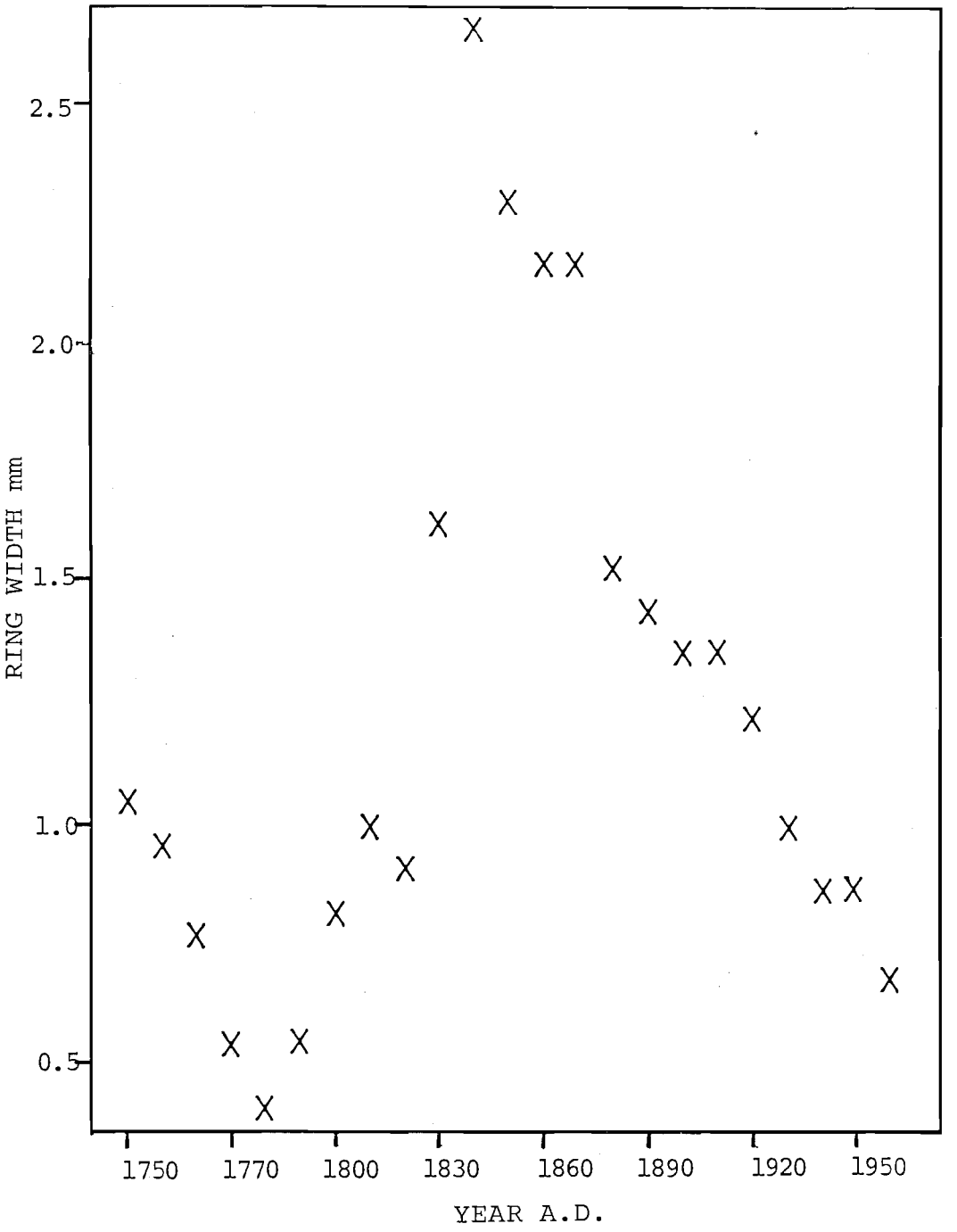


Figure 4.3 Example of plotted output from program RWLIST.

trend (signal *B*) and disturbance influences (signal *D*). Visual inspection and comparison of the growth characteristics of several specimens permits decisions to be made about use of all or portions of certain specimens and about the curve fitting procedure for each specimen in subsequent standardisation. Program RWLIST thus acts as a screen for all data to be used in the subsequent analysis.

4.3.3 Standardisation

The main purpose of standardisation is to remove non-climatic variance present in tree-ring series. This non-climatic variance is caused mainly by a decline in tree growth rate with age, the biological growth trend (signal *B*), and disturbance influences on growth (signal *D*), especially competitive suppression or release from competition, and the influence of insect attack, snow break and other factors on growth. Standardisation brings all ring width series to a uniform mean value. Thus, when several series are combined into a mean chronology, tree-ring series from fast growing trees will not dominate series from slower growing trees (Douglass 1936). Standardisation usually involves a curve fitting procedure, where the curve fitted approximates changes in growth associated with increasing tree age and disturbance influences. The measured ring widths (w_t) are converted to ring width indices (i_t) by dividing each width for year t by the expected growth (y_t, derived from the fitted curve) as follows,

$$i_t = \frac{w_t}{y_t}$$

Division by the expected growth both removes the growth trend and scales the variance so that it is approximately the same for the whole length of the series.

In early tree-ring studies, expected growth curves were hand-fitted and the ring width indices calculated manually (Stokes and Smiley 1968). These procedures have now been computerised in the INDEX program (Fritts 1976, Graybill 1979a, 1979b, 1982) which was used here. Four curve fitting options are available in this program,

(i) Horizontal line through mean.
(ii) Straight line of any slope.
(iii) Negative exponential curve.
(iv) Orthogonal polynomial curve.

The curve fit option to be used was decided upon after examination of the plotted 20 year averages for each series as produced in the RWLIST program. A curve was chosen that best approximated the long term (growth) trends in the tree-ring series.

Standardisation techniques were first developed with conifer species from low density stands in arid western North America. In these situations linear and exponential curve fits (Fig. 4.4) were found to best describe the underlying growth trends (Fritts 1976). Exponential curves are of the form,

$$y_t = ae^{-bt} + k$$

where a,b and k vary from series to series depending on the slope of the curve required to fit the data, e is the base of natural logarithms and y_t is the expected growth at a given year t (Fritts 1976). Often large ring widths are produced for the first 10 to 30 years in the life of the tree and this portion cannot be adequately fitted by the exponential curve. These early rings often provide the least reliable climatic information and can therefore be removed without any substantial information loss.

Some trees have a more gradual decline in growth rate with age and in such cases sloping straight lines are fitted. However, a horizontal line is often more appropriate than a sloping straight line as it helps preserve climatic trends that are equal to or longer than the series being standardised. This applies especially to shorter series. Horizontal lines are fitted when it is felt that there are no growth trends present in the tree-ring series, as is often the case with the outer sections of long lived species like bristlecone pine *(Pinus longaeva* and *P.aristata)* (Graybill 1982) and in some long lived New Zealand and Tasmanian trees (Dunwiddie 1982).

In recent years tree-ring research has been extended to dense, closed-canopy, mesic forests of eastern and northern North America and Europe, and in the Southern Hemisphere (Argentina, Australia, Chile and New Zealand). In these forests a great variety of non-climatic factors influence tree growth, resulting in a complex growth curve which cannot be adequately described by either the negative exponential or linear models. New curve fitting techniques have been developed to describe these more complex patterns.

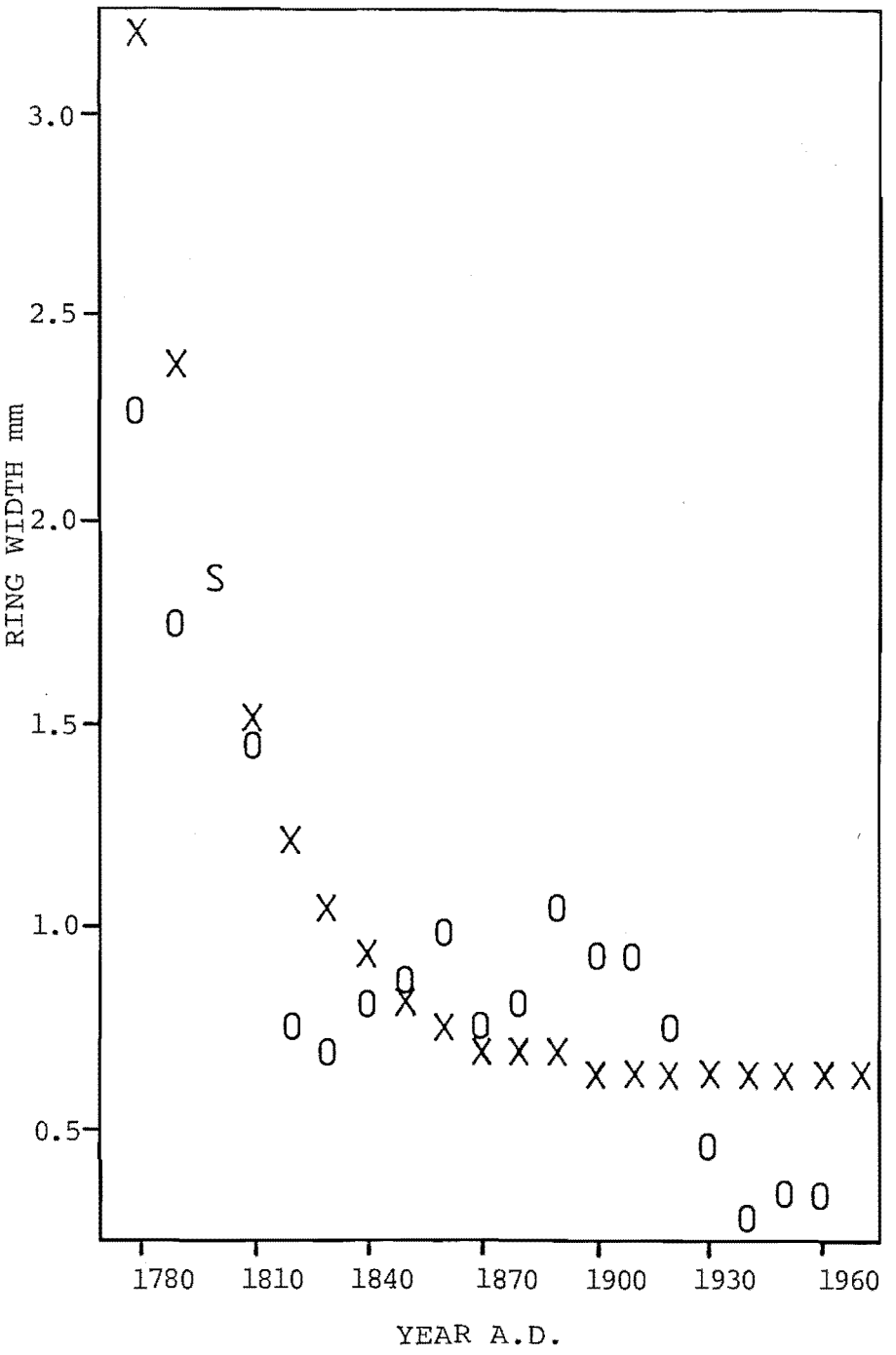


Figure 4.4 Example of plotted output from program INDEX showing exponential curve fit. O, observed values. X, exponential curve values. S, both values are the same.

Orthogonal polynomial curves using coefficients at progressively higher powers are used in the INDEX program to do this (Fig. 4.5). A univariate regression curve of the form,

$$y_t = a_0 + a_1x + a_2x^2 + \ldots\ldots a_mx^m$$

is fitted, where y_t is the expected growth for a given year, t, a_0 is a constant, a_1, a_2 ..... a_m are regression coefficients, and x is the ring width in year t (Graybill 1982). In cases where complex polynomial curve fits, using several coefficients, are employed to approximate the growth function, there is a risk that some climatic information will be removed, as this flexible curve fitting option begins to approximate shorter trends. Because of this possibility a test is made as each coefficient is added to the equation and the curve fitting procedure terminated when less than a specified percentage (usually 5%) of the variance is reduced by the addition of a further coefficient. Setting this at a lower value has the effect of forcing more coefficients into the equation, thus fitting the curve more closely to the data.

Some problems have been noted with the use of orthogonal polynomials. Often data in a small part of the series can influence the polynomial fit elsewhere and this can lead to distortion in the shape of the growth curve (Cook and Peters 1981). Also, to reduce the influence on the polynomial fit of erratic data points near the beginning and end of the data series, program INDEX artificially extends the series at each end. It has been suggested (Warren 1980) that this artificial extension often has an adverse effect on the curve fit. In an attempt to overcome these and other problems, two further methods of curve fitting have been developed.

A smoothing spline has been used by Cook and Peters (1981) and is considered superior to the orthogonal polynomial as it makes no assumptions about the shape of the curve. A smoothing spline can be envisaged as a series of cubic polynomial segments joined together. However, unlike ordinary polynomial curves, the behaviour of the spline in one area does not affect it elsewhere. The smoothing spline "provides a more natural fit to the data because it operates effectively as a centrally weighted moving average" (Cook and Peters 1981, p.52). The smoothing spline is similar to the digital filter (see Section 4.3.7) in its effect and provides a close fit to the

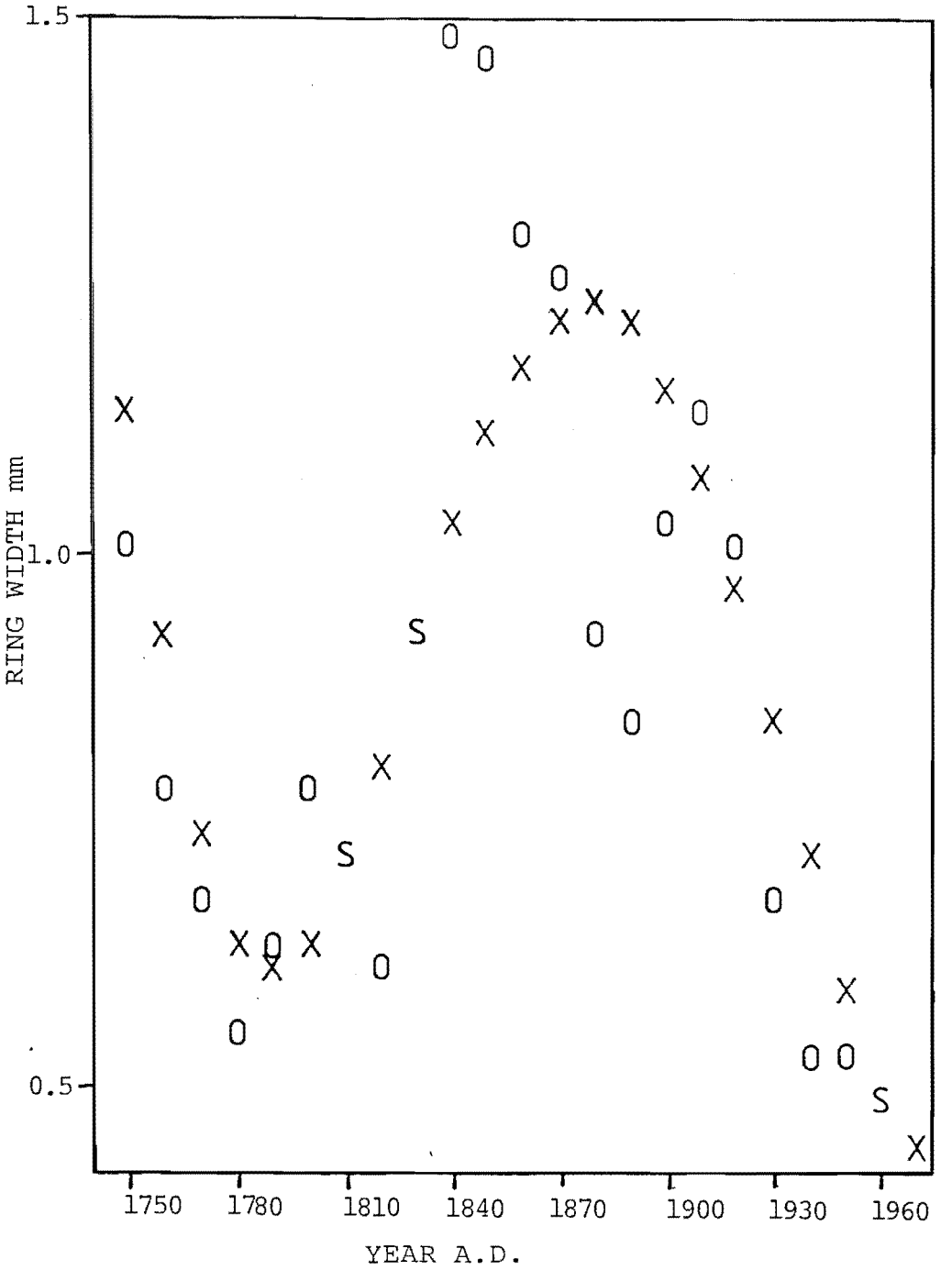


Figure 4.5 Example of plotted output from program INDEX showing polynomial curve fit. O, observed values. X, polynomial curve values. S, both values are the same.

tree-ring data. A second method uses a compound increment function (Warren 1980). This method describes the growth trend with an expression which has the form of an increment function. Periods of accelerated growth due to competitive interactions (i.e. signal *D*) are represented by additive components that have the same basic form. The compound increment function is still being tested but preliminary results (Warren and MacWilliam 1981) show that it is superior to the negative exponential for removing growth trends.

The orthogonal polynomial, smoothing spline and compound increment function curve fits were developed to remove the more complex growth trends in mesic forest trees, but despite these recent developments two basic problems still remain in the standardisation process,

(i) It is very difficult, in ring width series from mesic forest trees, to separate biological growth trends and disturbance effects from low frequency climatic trends and low intensity climatic effects. Complex curve fitting, whatever the method, will remove *all* of these. This is usually considered necessary and unavoidable, as it ensures that all growth trends and disturbance influences are removed, but often the low frequency or low intensity climatic effects are of interest. The use of less complex models (e.g. linear) will retain the non-climatic trends which may otherwise obscure climatic efforts.

(ii) Curve fits using orthogonal polynomials tend to fit tighter curves to shorter tree-ring series, relative to long series. Therefore in these shorter series the curve fitting is removing all variance except that at the highest frequencies, while in longer series more low frequency variance is being retained.

Because of these problems it was decided to test the effects of different curve fitting techniques and how they influence the final site chronology. The smoothing spline and compound increment function curve fitting methods are still being developed and were unavailable for use in the present study. The tests used the options available in the INDEX program.

Two tests were carried out. To test the effect of orthogonal polynomial curve fits on short series relative to long series, two long *Libocedrus bidwillii* tree-ring series were reduced in length by 100 year increments and after each reduction, orthogonal polynomial curves were fitted and the fits compared. In a second test to examine the influence of the different curve fit options in the INDEX program on resultant chronologies, tree-ring data from three sites (*Nothofagus menziesii*, NM; *N.solandri*, NS; and *L.bidwillii*, LB*) were standardised five times with the following options,

1. Horizontal line.
2. Straight line of any slope.
3. Negative exponential or straight line of any slope.
4. Orthogonal polynomial with curve fitting terminated when 10% or less of the variance was explained with the addition of a further coefficient into the equation.
5. Orthogonal polynomial with curve fitting terminated when 5% or less of the variance was explained with the addition of a further coefficient into the equation.

After standardisation each data set was processed in the SUMAC program (described in Sections 4.3.4 - 4.3.6) and various statistics calculated and compared. The data sets were also correlated with climate (see Chapter 7 for methods). The chronologies were plotted using program FILTER (described in Section 4.3.7) to assess differences in long term trends between the data sets. The curve fitting procedures used were based on the results of these tests, which are discussed in Chapter 5.

4.3.4 Index averaging

The next three sections describe the statistical analysis carried out by program SUMAC. The importance of averaging together many series of ring width or ring indice values has long been recognised

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* The LB chronologies were developed by combining tree-ring series from the CRC601 and TRK602 chronologies. The NM and NS chronologies were developed using many of the trees now incorporated into the OBL610 and ENT615 chronologies respectively.

(Douglass 1928). Averaging of several series from a site reduces the random growth signal (E) unique to each series and also other non-climatic influences on growth, while enhancing the common climatic signal. The derived tree-ring series from averaging are called *tree-ring chronologies*. In this study a unique chronology was developed for each site sampled, the *site chronology*. Various statistics were calculated for the site chronology. The three statistics most commonly used in evaluating tree-ring chronologies are mean sensitivity (described in Section 4.3.2), standard deviation and first order autocorrelation (Fritts and Shatz 1975).

The standard deviation of a tree-ring chronology is a measure of the scatter of data values around the mean. Standard deviation (s_x) is calculated as,

$$s_x = \sqrt{\frac{1}{n-1} \sum_{t=1}^{t=n} (x_t - \bar{x})^2}$$

where x_t is the width of the t-th ring in a series of n rings, and $\bar{x}$ the mean of the series (Fritts 1976). If the data are distributed normally then two-thirds of the data points are expected to lie within a distance of one standard deviation of the mean and in large samples, 95% of the data lie within two standard deviations of the mean.

First order autocorrelation (or serial correlation) measures the relationship between ring width in one year and that of the preceding year and is expressed as,

$$r_1 = \frac{1}{(n-1)s_x^2} \sum_{t=1}^{n-1} (x_{t+1} - \bar{x})(x_t - \bar{x})$$

where x_t is the width of the t-th ring in a series of n rings, s_x is the standard deviation and $\bar{x}$ the mean of the series (Pilcher and Gray 1982). Autocorrelation values range from -1.0 to +1.0. Negative values occur when wide and narrow rings alternate as was the case with *Phyllocladus glaucus* in New Zealand (Dunwiddie 1979), although such rings may not necessarily be annual. Autocorrelation is an indicator of the amount of long term trend in the series. Chronologies with high autocorrelation values often retain the most information on long term climatic trends although biological influences (e.g. leaf retention time) may also be important (LaMarche and Stockton 1974).

Generally there is an inverse relationship between mean sensitivity and autocorrelation in tree-ring chronologies, as mean sensitivity measures high frequency variance and autocorrelation measures low frequency variance. However, standard deviation is a measure of the total amount of ring width variation through time in the chronology.

4.3.5 Analysis of variance

Both analysis of variance and correlation analysis (described in the next section) are calculated for the period of time common to all series in the site chronology. To ensure that enough trees are included in these analyses the period is often only 100 to 150 years long. For the analysis of variance only trees from which two radii were crossdated and measured are used, thus some trees in the chronology are not used. The analysis of variance calculates the relative magnitude of the major sources of variance in tree-ring chronologies. A detailed discussion on the application of analysis of variance to tree-ring studies is presented in Fritts (1963, 1976). Four sources of variance commonly occur in site chronologies and the relative contribution of each of these is calculated and expressed by the percentage variance component. The first source of variance is that common to all series in the chronology (Y) and is assumed to reflect macroclimatic influences (Fritts 1976). Values in excess of 80% have been obtained from some arid sites but values are generally lower in mesic forest situations. An average value of 28% was obtained from 21 tree-ring chronologies developed in New Zealand mesic forests (LaMarche et al. 1979c) while an average value of 60% was obtained from 102 arid site tree-ring chronologies in western North America (DeWitt and Ames 1978). The second source of variance is due to variability between tree chronologies (YxT/G) and values increase as the heterogeneity of the site increases. The third source of variance comes from variability between cores within each tree and seldom exceeds a few per cent. Occasionally by chance, or by round-off error, these values can be negative. As long as these negative values are small they are replaced by zero values in the calculation of the percentage (Fritts 1976). The final source of variance is due to differences between the different series (YxCxT/G)and in unrelated series (e.g. developed from random numbers) this value should be close to 100%. If two or more sites are analysed, variance due to differences between the two sites can also be calculated.

Two points arise from the use of analysis of variance with tree-ring chronologies. Firstly the various assumptions of the analysis of variance model are not always met when using tree-ring series and the results are therefore not used for hypothesis testing (Graybill 1982). The percentage variance values are thus only used as descriptive statistics for chronology evaluation. One assumption not met is the need for random sampling (Sokal and Rohlf 1973). Because of the aims of dendroclimatology, selection of trees for sampling is based on apriori assumptions so as to maximise the climatic signal (component Y of the analysis of variance, see Chapter 3). Secondly the analysis of variance (and also the correlation analysis) is calculated for the period common to all (or most) trees, usually within the most recent 150 years. If climatic conditions have been significantly different in the past, then the relative magnitude of the four sources of variance may well differ. Hughes et al. (1978) showed that for the period 1875-1900, the common variance was 6% greater than for the period 1905-1930 A.D. This higher common variance during the earlier period was thought to reflect a known period of greater climatic variability.

The number of samples needed for optimising the climatic signal (Y) relative to the non-climatic "noise" can be calculated. The ratio of signal to noise (S) in a site chronology varies directly with the number of trees (n) that are included and can be calculated as (Graybill 1982),

$$S = nY/(100-Y)$$

As the number of trees collected increases, the percentage variance due to non-climatic factors decreases and the signal-to-noise ratio increases (DeWitt and Ames 1978). From the above equation the number of trees required for any particular signal-to-noise ratio can be calculated as,

$$n = S\ (100-Y)/Y$$

DeWitt and Ames (1978) suggest that a value of 15 is desirable for the signal-to-noise ratio, but lower values have produced acceptable climatic information (e.g. Pilcher and Gray 1982).

4.3.6 Correlation analysis

Correlation analysis in the SUMAC program examines the co-variance that occurs between different tree-ring series in a chronology. The correlation coefficient measures interdependence between two data sets (x_t and y_t) and is used to measure association between two time series. The correlation coefficient r_{xy} is calculated as,

$$r_{xy} = \frac{\sum_{t=1}^{t=n} (x_t - \bar{x}_x)(y_t - \bar{x}_x)}{(n-1)s_x s_y}$$

where $\bar{x}_x$, $\bar{x}_x$, s_x and s_y are the means and standard deviations of the two data series and n is the number of items compared. Correlation values are closely related to the common variance (Y) in the analysis of variance and when analysis of variance cannot be used, the average correlation value for all series can be substituted (Fritts 1976). Two sets of data are usually examined in the correlation analysis; all the individual series, and the combined tree chronologies (consisting of the average of two series each). A matrix of correlation coefficients for each combination and the average of all the series is calculated. This is undertaken for the same time period as used in the analysis of variance and can also be undertaken for specified subperiods (e.g. 10 or 20 years) if required. The last option allows changes in co-variance between trees through time to be detected and such changes may be related to climate. Standard deviation, mean sensitivity and autocorrelation values are also calculated for the whole period and for subperiods.

As in the analysis of variance, the correlation coefficients are only descriptive statistics and no significance levels are calculated (Graybill 1982). The correlation analysis provides the last check for aberrant specimens in tree-ring chronologies. Series that correlate poorly with other series can be identified and removed, or it may be found that the curve fitted for standardisation was not appropriate and a more appropriate curve can be fitted.

4.3.7 Filtering

A computer program (FILTER) was developed during this study to plot tree-ring chronologies and to enhance variance at particular

frequencies using a digital filter. This program is presented and discussed in Appendix 3. Digital filters have been developed for tree-ring research and meteorological studies and pass variance at a variety of frequencies. LaMarche and Fritts (1972) used four digital filters, including the one used here, to examine variance at different frequencies in tree-ring chronologies. Enhancement of variance at particular frequencies is important for investigating environmental influences on tree growth (e.g. short-term variations may reflect local conditions while long term trends may reflect regional climate). A discussion of how filters function is included in Appendix 3. A *Nothofagus solandri* chronology (MTB613) was tested, using these four filters (filter weights are listed in Table 4.1). The effect of the filtering is illustrated in Fig. 4.6. The frequency response curves for the four filters are shown in Fig. 4.7. The high-pass filter only passes variance of less than 10 years (high frequency variance). The 11-year band pass filter retains variance with periods of between 6 and 15 years and the low-B filter eliminates all but the lowest frequency variance (greater than 20 to 30 years). The low-A filter which passes variance greater than 10 years while excluding all higher frequency (i.e. less than 10 years) variance (Stockton and Fritts 1971) proved to be most suitable for the present study. All chronologies developed here were filtered using the low-A digital filter in order to identify and evaluate long term trends in the chronologies.

TABLE 4.1 Weights used in the four digital filters tested in Section 4.3.7 (after LaMarche and Fritts 1972).

Weight Number	High-Pass	Low-A	11-Year Band Pass	Low-B
0	0.7744	0.2256	0.1360	0.0798
±1	-0.1933	0.1933	0.1070	0.0782
±2	-0.1208	0.1208	0.0340	0.0737
±3	-0.0537	0.0537	-0.0460	0.0667
±4	-0.0161	0.0161	-0.0950	0.0581
±5	-0.0030	0.0030	-0.0980	0.0486
±6	-0.0003	0.0003	-0.0620	0.0390
±7			-0.0190	0.0301
±8			-0.0230	0.0223
±9			0.0380	0.0159
±10			0.0340	0.0109
±11			0.0230	0.0071
±12			0.0130	0.0045
±13			0.0070	0.0027
±14			0.0030	0.0016
±15			-0.0010	0.0007
±16			-0.0060	
±17			-0.0080	
±18			-0.0090	
±19			-0.0060	
±20			-0.0040	
±21			-0.0010	

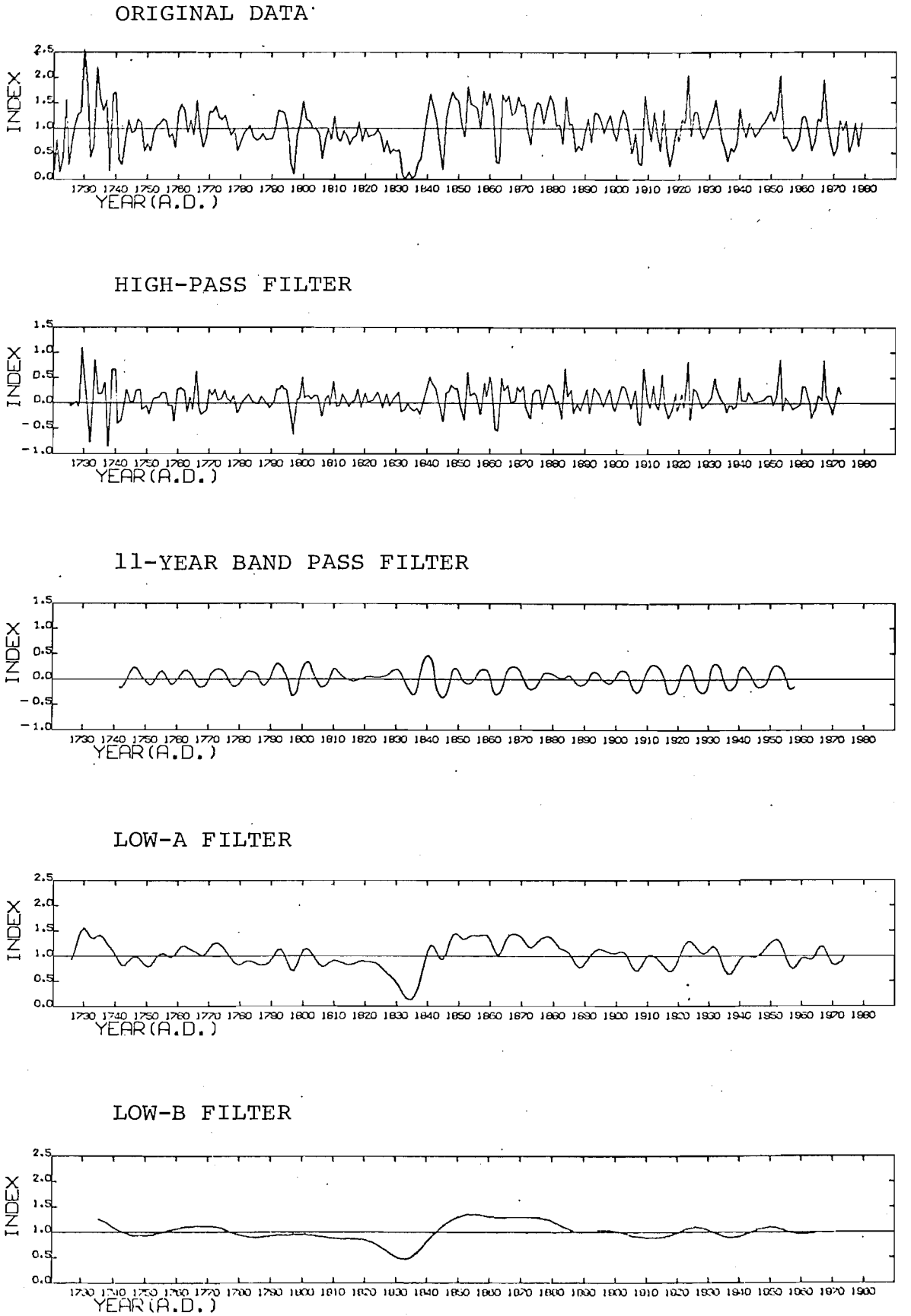


Figure 4.6 Filtered tree-ring series derived using the four different digital filters discussed in Section 4.3.7.

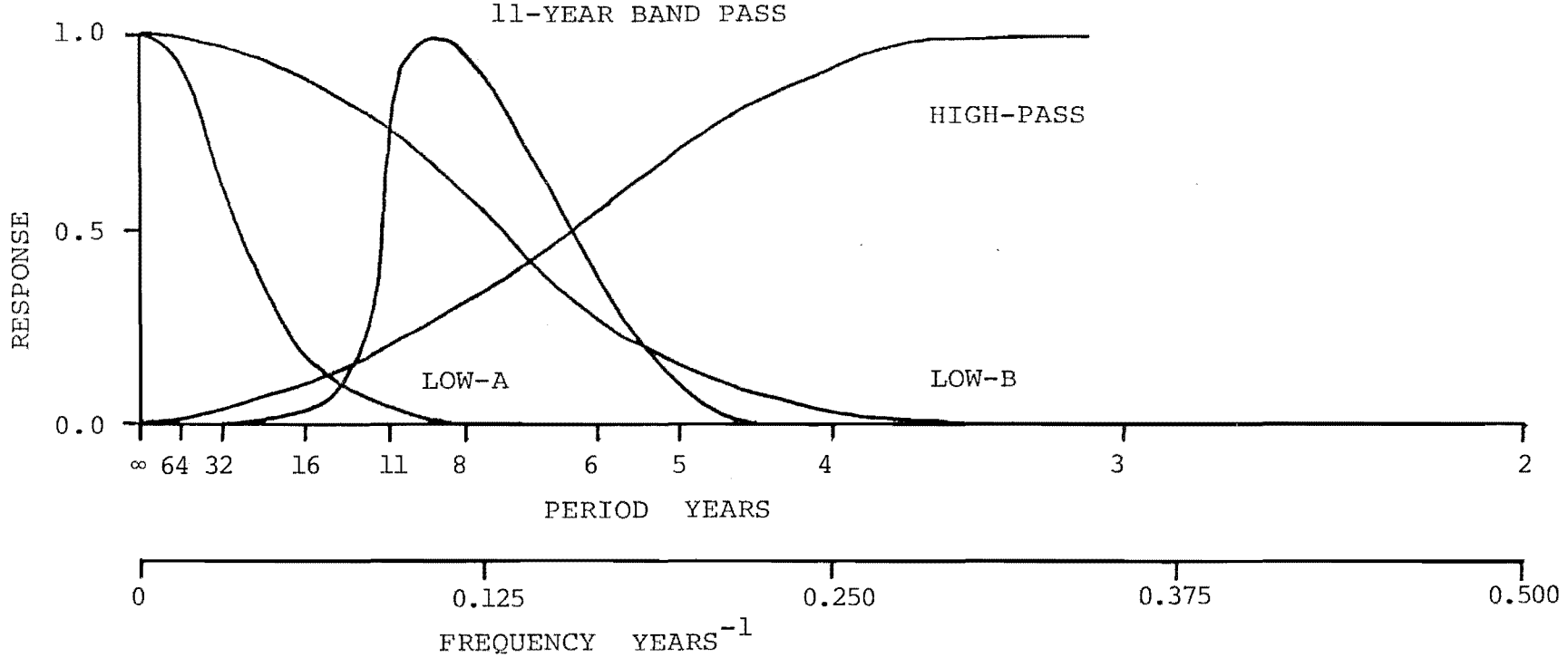


Figure 4.7 Frequency response functions for the four digital filters used in Section 4.3.7 (after LaMarche and Fritts 1972).

CHAPTER FIVE

CHRONOLOGY BUILDING

5.1 GROWTH RING CHARACTERISTICS AND CROSSDATING

5.1.1 *Libocedrus bidwillii*

Many of the cored *Libocedrus bidwillii* trees were of no value for crossdating because of the occurrence of both heart rot (in 69% of the sampled trees) and lobate growth. The high incidence of heart rot reflects, in part, the large sample size; had only a limited number of trees been cored, rotten trees would have been avoided. Dunwiddie's observation (1979) that heart rot is almost universal in mature trees is supported by this study. Other studies of this species (e.g. Druce 1966, Clayton-Greene 1977, P. Wardle 1978) have not commented on the frequency of heart rot.

Lobate growth occurs frequently and is associated with ring wedging. This was often difficult to detect externally. Examination of discs showed that ring wedging results in the local suppression of groups of rings. The failure to crossdate many cores was almost certainly due to ring wedging effects. Lobate growth has been related to the development and death of major branches and to consequential variations in food and growth regulator supplies (Fritts et al. 1965). Much of the lobate growth in *Libocedrus bidwillii* could be due to similar processes as often in this species only a few branches support the majority of the foliage and dead branches are common. Dunwiddie (1979) noted that ring wedging was worst at stressed subalpine sites. Very gnarled trees at higher altitudes were not sampled here for this reason.

False rings and locally absent rings were uncommon and easily detected. In sampled trees the percentage of locally absent rings was 0.23%. The boundary between the latewood and the earlywood was distinct. Bands of cells with dark intracellular contents were encountered in some rings but careful examination of cell dimensions allowed the separation of these bands from normal latewood. Patel (1968) commented that this dark colouration occurs frequently in New Zealand conifers.

Libocedrus bidwillii ring width series were complacent, occasionally to the extent of having only one or two signature rings every 50 rings. Despite this, crossdating was achieved and two chronologies developed. One chronology used trees from two adjacent sites. A chronology was not developed for a fourth site (HTB), although the trees crossdated with the other sites.

5.1.2 *Nothofagus menziesii*

Sampled *Nothofagus menziesii* trees were rarely rotten, although many old, gnarled and obviously rotten trees were deliberately not sampled. A distinctive feature of many *N.menziesii* trees was the occurrence of bands of very narrow growth rings (often from 20 to over 100 rings wide) in the outer sections of older trees. Many growth rings were absent. Those present were only one or two cells wide in these bands, and crossdating was usually impossible. These difficult bands were especially common in trees close to timberline (above 1000 m)and were largely absent from trees at lower altitudes (800 m - 1000 m).

Nothofagus menziesii growth rates decline with altitude and in South Westland and Fiordland are commonly less than 0.5 mm per annum in trees near timberline (Herbert 1973, P. Wardle 1980a). Growth rates in the outer sections of old trees are often considerably slower than this. The bands of very narrow growth rings observed, probably relate to slow growth rates in older trees, to growth suppression by younger and more vigorous trees, and to crown damage through snow break and other similar phenomena. The regular occurrence of these bands was a conspicuous feature of the highest sites examined (CMF, HRS, KEY) and prevented the crossdating of radii from these sites. Sites at slightly lower altitudes lacked these bands and crossdating was readily achieved.

Occasional ring wedging was observed, with two or three rings terminating and becoming locally absent for a portion of the tree's circumference (Fig. 5.1a). This problem was not serious and the percentage of locally absent rings was 0.42%. False rings were not observed and the boundary between the latewood and the earlywood was distinct. The ring width series were moderately sensitive with regular occurrence of signature rings. Although trees growing close to

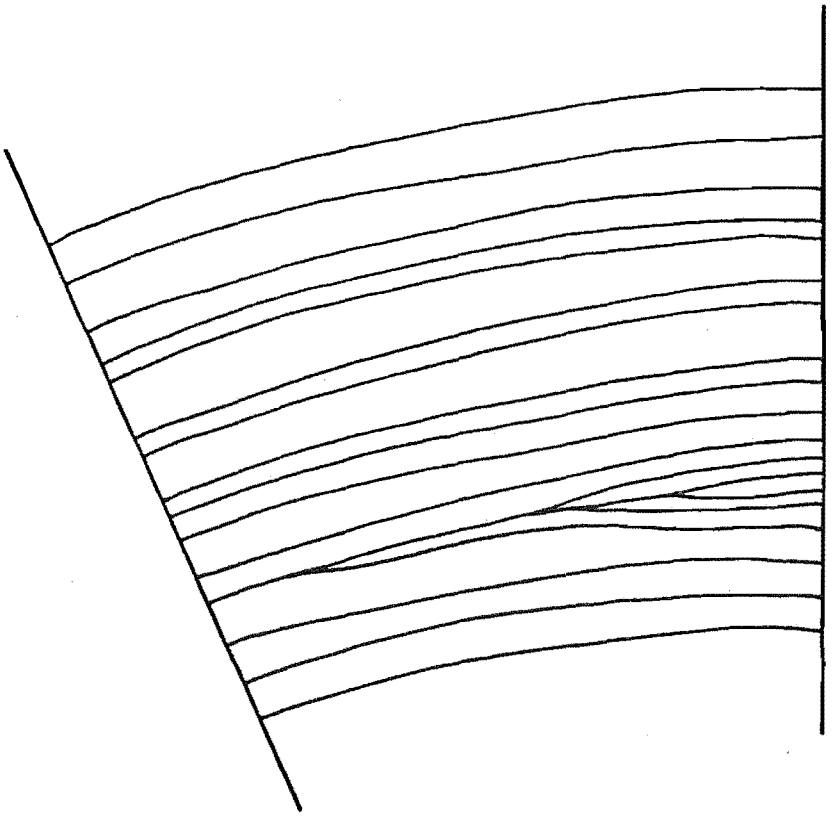


Figure 5.1a Ring wedging in a *Nothofagus menziesii* tree.

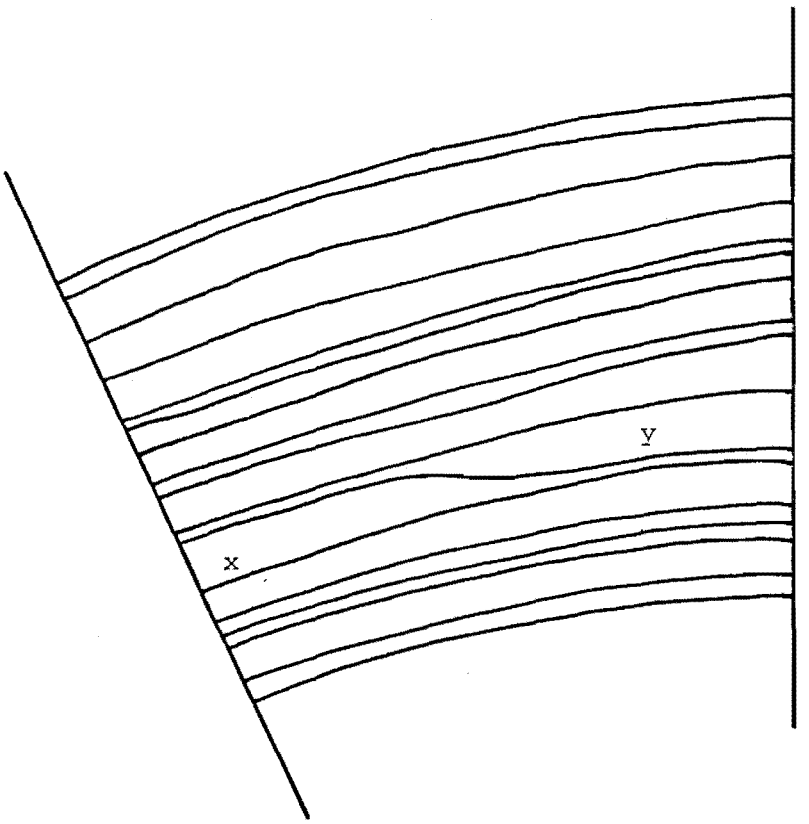


Figure 5.1b Meandering growth ring in a *Nothofagus solandri* tree. Ring x is initially wide and then narrows, while ring y, initially narrow, widens.

timberline could not be crossdated, crossdating was otherwise good and five chronologies (KEA, LKE, OBL, UHV, UTV) were developed.

5.1.3 *Nothofagus solandri*

Nothofagus solandri was the most easily crossdated of the three species; few problems were encountered with this species. Rotten-hearted trees were rare at the sites studied, and growth rings distinct. Although missing rings occurred frequently (1.35%) they were easily detected through crossdating. Bands of narrow and absent rings were uncommon. Ring wedging was rare, but occasionally a narrow ring would widen and the adjacent wide ring narrow - a meandering growth ring (Fig. 5.1b). The physiological basis for this is unknown and warrants further study. Signature rings and ring patterns were common and very distinctive, greatly facilitating crossdating. False rings occasionally occurred when a row of small vessels were laid down in the middle of a growth ring. These vessels were usually smaller than those at the start of each growth ring and were easily detected. They probably occurred after temporary growth cessation due to a period of cooler temperatures in mid summer or after some other form of environmental limitation. In Chapter 2, radial growth was shown to be closely related to temperature. Schweingruber (1980) has related the occurrence of false rings in several conifer species to the number of cold days during the growing season.

Nothofagus solandri ring width series were sensitive and cross-dating was achieved at all sites sampled, except for the low altitude site near Lake Te Anau.

5.2 STANDARDISATION

5.2.1 Influence of sequence length

The rationale for standardisation has been discussed in Chapter 4 and two tests to assess the affects of standardisation on the development of tree-ring chronologies, outlined. The results of the first test are presented here and of the second test in Section 5.2.2. The standardisation procedure used in the present study is then outlined.

The standardisation curves fitted to progressively shorter tree-ring series derived for one *Libocedrus bidwillii* tree are

presented in Fig. 5.2. The top curve is for 20 year means plotted at 10 year intervals for the complete series with the curve fitted using the polynomial curve fit option, superimposed. Each of the lower curves has been shortened by 100 years and the standardisation curve re-fitted. For the period 1850 to 1978, common to all series, the curve fitted in standardisation becomes progressively tighter as the overall series length decreases. For example, in Fig. 5.2, the polynomial curve fitted to the 129 year series almost approximates the 20 year tree-ring means, while in the 429 year series, only a sloping line was fitted to this same portion of the series. This overfitting of shorter series relative to longer series could result in the removal of more long term climatic trend in chronologies composed of predominantly short (100 to 150 years) series while chronologies with proportionally more longer series will retain more of this trend. This problem will be particularly acute when using short series derived from the outside of much older trees.

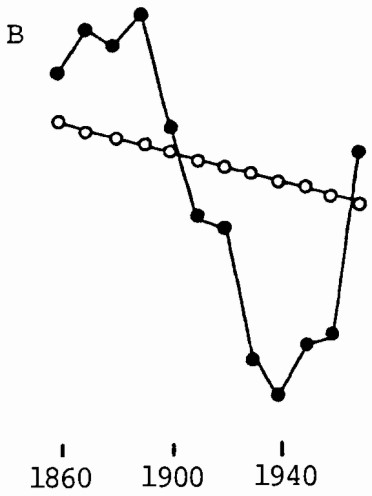
Ideally a tree-ring chronology should be composed of ring width series of equal length and extending to the tree centre, but in practice this is not usually undertaken. Problems with the over-fitting of curves to short tree-ring series was alleviated by using horizontal lines for standardisation of these series or, if a known growth trend was present (i.e. the ring series extended to the tree centre), by using polynomial curves with curve fitting terminated at the 10% level (see Section 4.3.3). This latter procedure was found very useful in approximating the growth trend in many series without removing higher frequency variation.

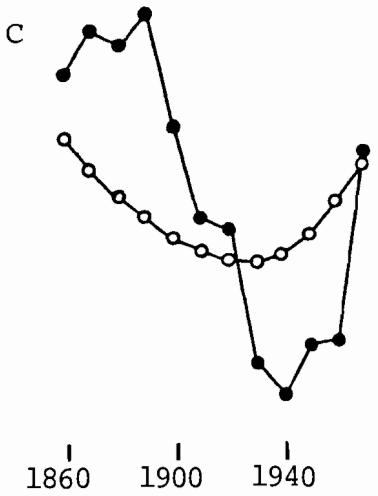
5.2.2 Influence of different curve fit options

The chronologies developed using the different curve fit options discussed in Chapter 4 are referred to by species codes (LB, *Libocedrus bidwillii;* NM, *Nothofagus menziesii;* NS, *N.solandri*) and by curve fit option codes (1, horizontal line; 2, straight line of any slope; 3, negative exponential or straight line; 4, orthogonal polynomial with curve fitting terminated when 10% or less variance is explained by addition of a further coefficient; 5, as in 4 but terminated at 5%. NM-3 is identical to NM-2 as program INDEX was unable to fit negative exponential curves to any tree-ring series in this chronology, fitting straight lines instead. The 5 options used are a series of tighter curve fits from horizontal straight lines (option 1) to high order orthogonal polynomial curve fits (option 5).

Figure 5.2 The influence of ring width series length on the fitting of polynomial curves in standardistion. Twenty year mean values at ten year intervals for the complete series are plotted in A. The four lower curves (B-E) represent the 1850-1978 period of the top curve and have polynomial curves superimposed on them (N.B. the vertical scale has been increased). The polynomial curve was determined for the full top curve (B) and then for the top curve shortened by 100 year increments (C-E). Only the 1850-1978 period is plotted.


A
1550
1600
1650
1700
1750
1800
1850
1900
1950


B
1860
1900
1940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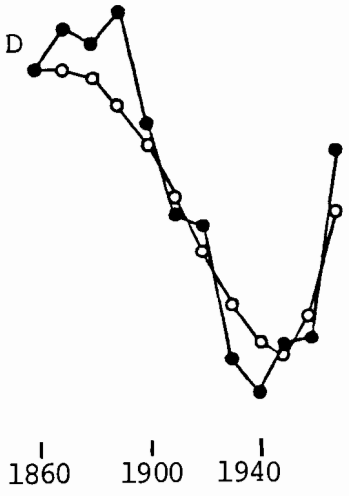
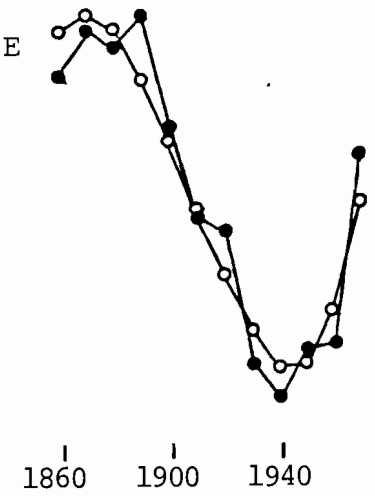

D
1860
1900
1940


E
1860
1900
1940

The statistical characteristics of each of these tree-ring chronologies are presented in Table 5.1, and the filtered chronologies (options 1 and 5 only) plotted in Fig. 5.3. Mean sensitivity, standard deviation and autocorrelation are commonly used statistics to describe tree-ring chronologies (Fritts and Shatz 1975). A decline in autocorrelation occurs as the curve fits become tighter, reflecting a reduction in the amount of low frequency variance (trend) retained in the chronologies. However, mean sensitivity, measuring year to year variation, remains constant and does not appear to have been affected by curve fitting. Standard deviations are larger for the less tight curve fits (options 1 and 2 especially) indicating a greater scatter of data points in these cases. From these results it would seem that the tighter curve fits (options 4 and 5) reduce persistence in the tree-ring chronologies, in a fashion somewhat similar to some digital filters. Associated with this is a reduction in overall variance of the chronology. Year to year (high frequency) variance is largely unaffected.

The analysis of variance, correlation analysis and response function analysis results show few clear trends, both within each species and between species (Table 5.1). In the NM chronologies, common variance is greatest in the NM-4 and NM-5 cases, for the NS chronologies it is greatest in NS-1 and for the LB chronologies, greatest in LB-3. However, the differences present are not great, the largest being 7.4%. The per cent variance explained by climate in the response function analysis also shows few trends, except for an unexpected inverse relationship with chronology common variance. The plotted response functions (Fig. 5.4) are consistent in shape between the different options in the NM and LB cases. Some small differences in the NS chronologies (e.g. no significance attached to February and March temperature in NS-1, NS-2 and NS-3, while these months are significant in NS-4 and NS-5) could be related to tree response to climate at different frequencies, a phenomenon recently commented on in the literature (e.g. Guiot et al. 1982) and discussed further in Chapters 7 and 8. Lawson et al. (1980) found that by analysing response functions based on two or more curve fitting options, they were able to distinguish between climatic and non-climatic influences on growth. The chronology they developed was, however, from an area with a known fire history and changes in the response functions could be related to known changes in understorey vegetation composition and resultant competition changes. In the

TABLE 5.1 Statistical characteristics of the tree-ring chronologies developed using different curve fit options in program INDEX.

Code[1]		AC[2]	SE[3]	MS[4]	%Y[5]	XCOR[6]	%C[7]
NS	1	0.67	0.10	0.38	56.7	0.61	27.5
	2	0.63	0.10	0.38	50.3	0.55	32.9
	3	0.63	0.09	0.38	50.7	0.56	32.5
	4	0.59	0.09	0.38	49.3	0.56	34.4
	5	0.54	0.09	0.38	50.3	0.57	35.0
LB	1	0.77	0.12	0.17	33.1	0.36	53.1
	2	0.75	0.11	0.17	33.3	0.35	53.0
	3	0.75	0.11	0.17	34.0	0.35	52.7
	4	0.69	0.11	0.17	32.9	0.35	55.0
	5	0.69	0.11	0.17	31.1	0.33	57.0
NM	1	0.43	0.13	0.31	22.1	0.24	67.6
	2	0.42	0.12	0.31	22.0	0.25	68.7
	3	0.42	0.12	0.31	22.0	0.25	68.7
	4	0.41	0.11	0.31	23.7	0.26	65.9
	5	0.39	0.11	0.31	26.6	0.30	66.9

Notes:
1. Chronology code as used in text
2. Autocorrelation
3. Standard error
4. Mean sensitivity
5. Common variance in ANOVA
6. Correlation coefficient between all series
7. Variance attributable to climate in response function

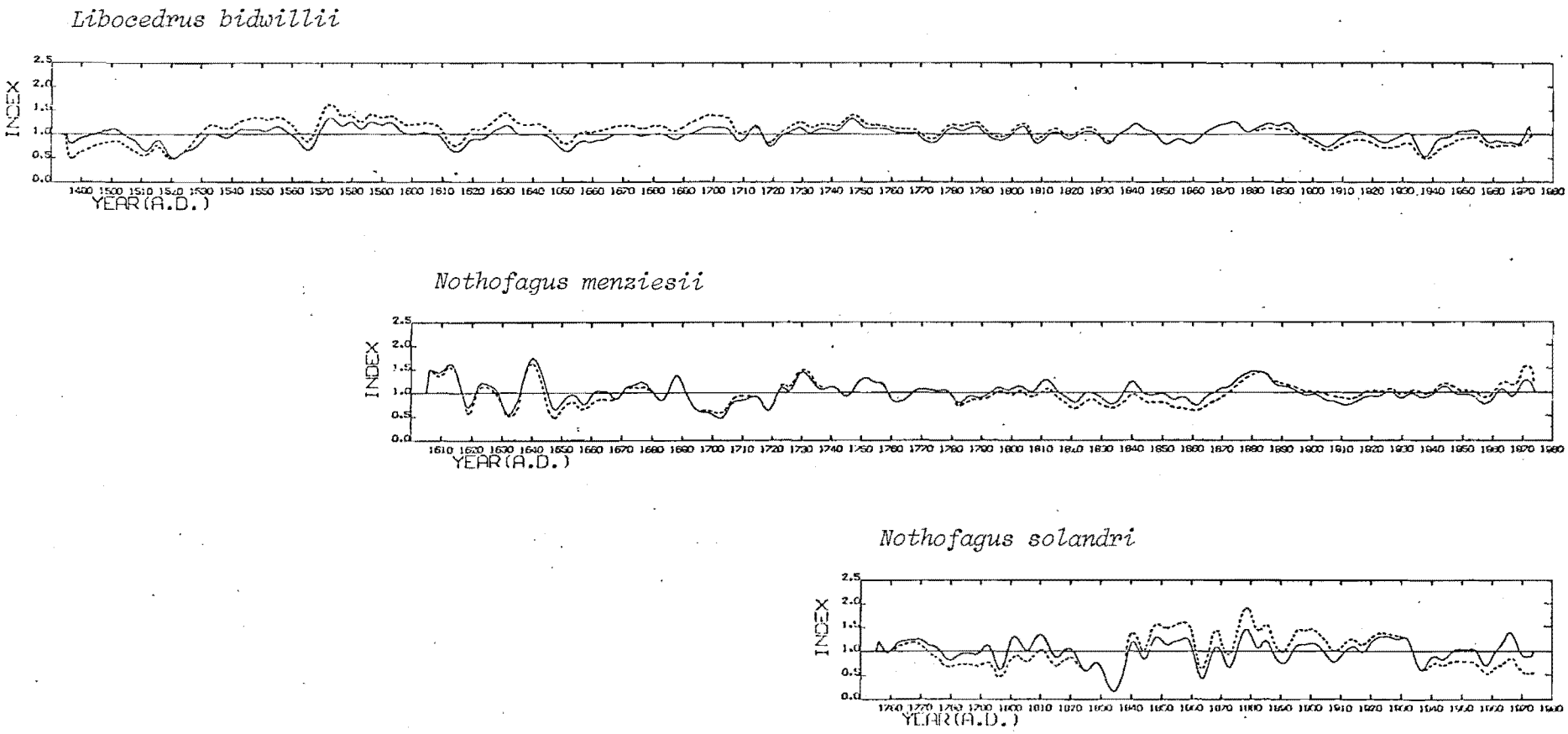
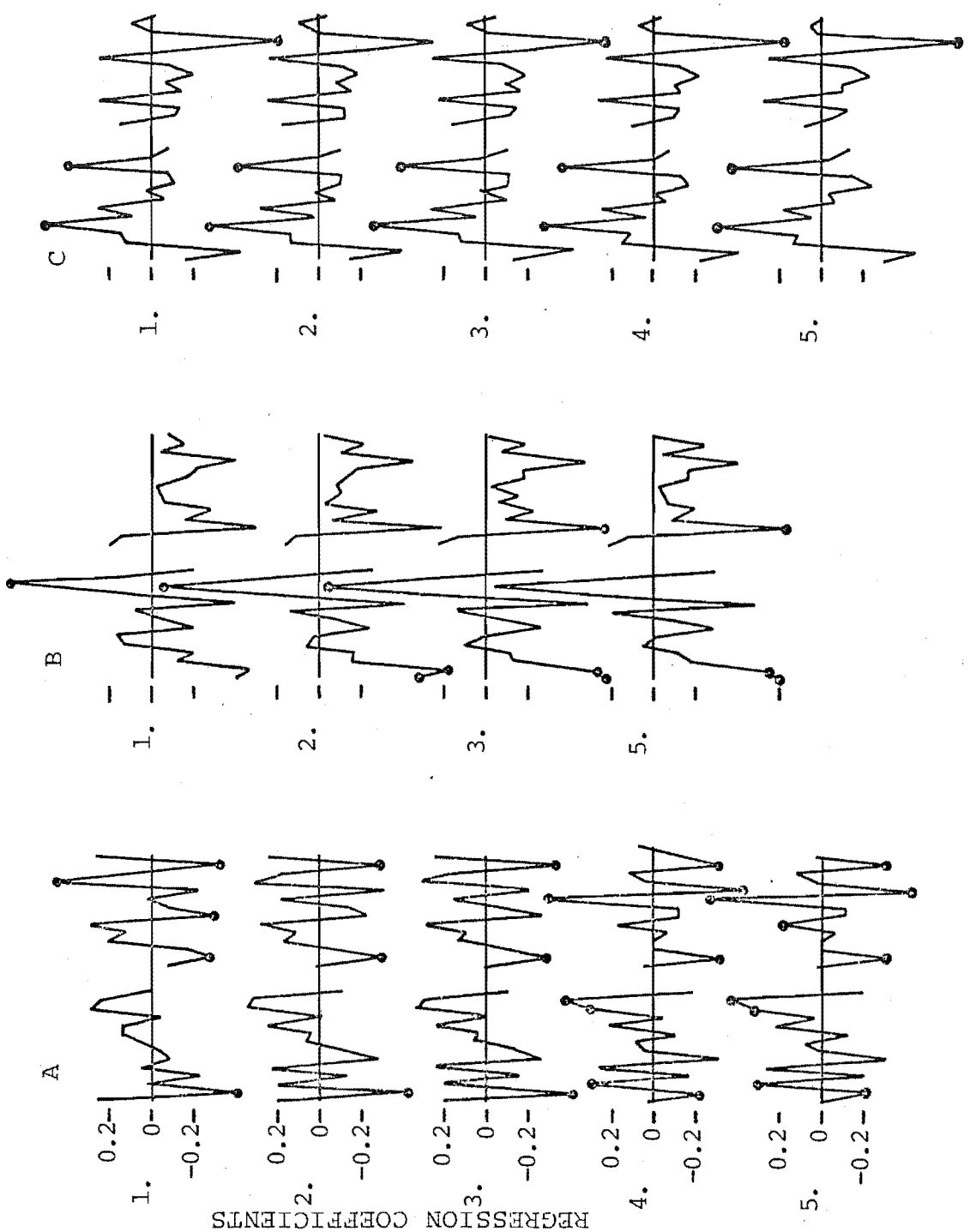


Figure 5.3 Filtered curves for three species derived using option 1 and option 5 curve fitting procedures in standardisation. -------- option 1; ———— option 5.

Figure 5.4 Response functions for chronologies from *Nothofagus solandri* (A), *N.menziesii* (B) and *Libocedrus bidwillii* (C) trees developed using five different curve fitting options in standardisation. Significant response function coefficients are marked with a black circle. 1.-5. are the different curve fit options.



mesic forests of New Zealand similar processes (e.g. insect epidemics) are less easy to detect and historical records largely lacking.

Filtered curves for the option 1 and option 5 chronologies for each site (Fig. 5.3) represent the extremes. Filtered curves for the chronologies developed, using the other options, are of intermediate form. Differences between the two options probably reflect growth trends, which have been retained in the option 1 fit, but not in the option 5 fit. Low index values in the last few decades of the NS-1 chronology reflect slow growth in old trees, while growth is rapid when the trees are younger (in the middle portions of the chronology). Low index values at the start of the NS-1 chronology are for only a few trees and reflect slow initial tree growth. These growth patterns have been removed from the NS-5 chronology. Age-dependent growth effects are generally very pronounced with this species. Similar patterns are present in the LB chronologies and can again be explained in terms of growth trends. The situation is less clear in the NM chronologies and the curve fits differ little in their effects, indicating the occurrence of little growth trend with this species.

5.2.3 Discussion

Although differences occur between the chronologies developed using the different curve fit options, they are not great. This is in agreement with the results of two other studies (Hughes et al. 1978, Lawson et al. 1980) which also found only small differences between chronologies developed using different curve fit options. Hughes et al. (1978) considered the polynomial option best as it was a "realistic ecological model of annual radial increment" while Lawson et al. (1980) considered it best to use both chronologies developed by standardisation with and without polynomials. However, in analysing a large number of chronologies, as in the present study, the computing costs involved in standardising every chronology in at least two different ways, becomes prohibitive.

Here, standardisation involved the use of a mixture of curve fits, using all five options. The standardisation procedure used is set out below.

(i) The complete data set (as plotted by RWLIST) was inspected and common trends noted. These were assumed to be age dependent (occurring at similar *relative* stages in the tree life) or climatic (occurring at the same chronologic time independent of tree age).

(ii) The oldest series were used as reference series and these were assumed to have an overriding growth trend superimposed on a shorter climatic trend.

(iii) Trends apparent in all other (shorter) series were considered in relation to the longest series and also to the tree age (if known).

(iv) Curves which seemed to best approximate the underlying growth trend were fitted. Where possible polynomial curve fits were not used on shorter series.

(v) Curve fits were also fitted independently by an experienced second worker and compared. All disagreements were re-examined and re-fitted as appropriate.

(vi) After running program INDEX, the plotted curve fits were inspected for poor fits and if necessary, curves re-fitted.

(vii) Correlation values obtained in program SUMAC were also checked and curve fits of poorly correlated specimens were carefully checked.

(viii) The series were then re-analysed with the re-fitted curves.

Although not ideal, the above method was found adequate for the purposes of the present study, especially when one considers the small differences in the per cent variance explained by climate in the tests. It was also found that removal of poorly correlated series from the chronologies resulted in much greater increases in common variance than the use of the different curve fits.

5.3 WITHIN-TREE GROWTH RING VARIABILITY

5.3.1 Circuit Uniformity

Environmental and physiological processes can cause the pattern of narrow and wide growth rings along several radii around the circumference of a tree to vary. Visual examination of many cross-sections from the species investigated indicated, when ring wedging was absent, that circuit uniformity was good. This was tested statistically by comparing the pattern of narrow and wide growth rings between different radii at the same height in the tree bole. Four radii, at approximately 90^{o} from each other, were measured and the standardised ring width series compared using the product-moment correlation coefficient.

Average correlation coefficient values of 0.78 (n=87 years, range 0.76 - 0.83) and 0.69 (n=87 years, range 0.53 - 0.79), 0.62 (n=71 years, range 0.50 - 0.76) and 0.53 (n=140 years, range 0.27 - 0.67) were obtained, respectively, for two *Nothofagus solandri* trees, one *N.menziesii* tree and one *Libocedrus bidwillii* tree. All the observations are highly significant ($P < 0.001$) confirming the observation made above. Although some crossdating difficulties are introduced by lobate growth, ring wedging and bands of very narrow rings, circuit uniformity is generally good in the three species examined.

5.3.2 Vertical Uniformity

The pattern of narrow and wide growth rings can also change with height in the tree. Such changes reflect, to a large extent, the distance between the actively photosynthesising tissue and the point where the growth ring is being formed. In mature trees from closed stands, ring width tends to be greatest near the zone of maximum foliage, while a second, lesser, maximum can occur at the base of the bole because of root buttressing effects (Farrar 1961). To assess whether the pattern of narrow and wide growth rings varied with height in the tree bole, ring widths were measured at 1 m intervals up the bole of a *Nothofagus solandri* tree (nine heights) and a *Libocedrus bidwillii* tree (five heights). Bands of very narrow rings in the sampled *N.menziesii* trees prevented analysis of this species. Ring widths for the last 140 years were measured on one radius at each height. Various statistics were calculated for each series and the similarity between the series assessed using the product-moment correlation coefficient.

Average correlation values of 0.69 (n=140, range 0.55 - 0.77) and 0.57 (n=140, range 0.35 - 0.80) were obtained from the *Nothofagus solandri* tree and *Libocedrus bidwillii* tree respectively. All the correlations are highly significant ($P < 0.001$). 20 year means for radial growth (non-standardised values) at each height are plotted in Fig. 5.5. Variations with height of mean ring width, per cent locally absent rings, mean sensitivity and autocorrelation, are given in Fig. 5.6.

Inspection of Fig. 5.5 shows that although absolute ring width may vary with height, the trend in mean ring width is similar and the correlation analysis confirms this. Fritts et al. (1965) also observed similar trends at different heights in four *Pinus ponderosa* trees from semi arid sites in western North America and obtained highly significant correlation coefficients for these. Variations in ring width at six different heights were uniform and the magnitudes similar in seven to eight trees from one *Picea abies* stand and two *Fagus silvatica* stands in Denmark (Holmsgaard 1955). However, the ring variations in the *F.silvatica* trees indicated that the strongest relationship between ring width and climate occurred some distance above breast height. Trend in mean ring width of five *Quercus petraea* trees from North Wales was less similar (Hughes 1982) but no other details were given. From the results presented here, it would seem that unless some exceptional event had influenced a tree (e.g. major branch breakage), trends in ring width are similar at different heights in *Nothofagus solandri* and *Libocedrus bidwillii*. This also probably applies to *N.menziesii* as distinctive signature ring patterns were noted at different heights in the trees examined.

The statistics presented in Fig. 5.6 relate to tree growth during the last 140 years at each height (i.e. actual years of formation are constant), rather than to tree age which was not investigated. The only trend common to both trees is a decline in mean sensitivity with height. The percentage of locally absent rings also declines with height in the *Nothofagus solandri* tree, and closely parallels the variation in mean sensitivity. No absent rings occurred in the *Libocedrus bidwillii* tree, their occurrence was low in this species generally (0.23% c.f. 1.35% in *N.solandri)*. Mean sensitivity is in part dependent on the number of absent rings and a large percentage of absent rings would increase the mean sensitivity value. Fritts et al. (1965) also found a close relationship between these two statistics.

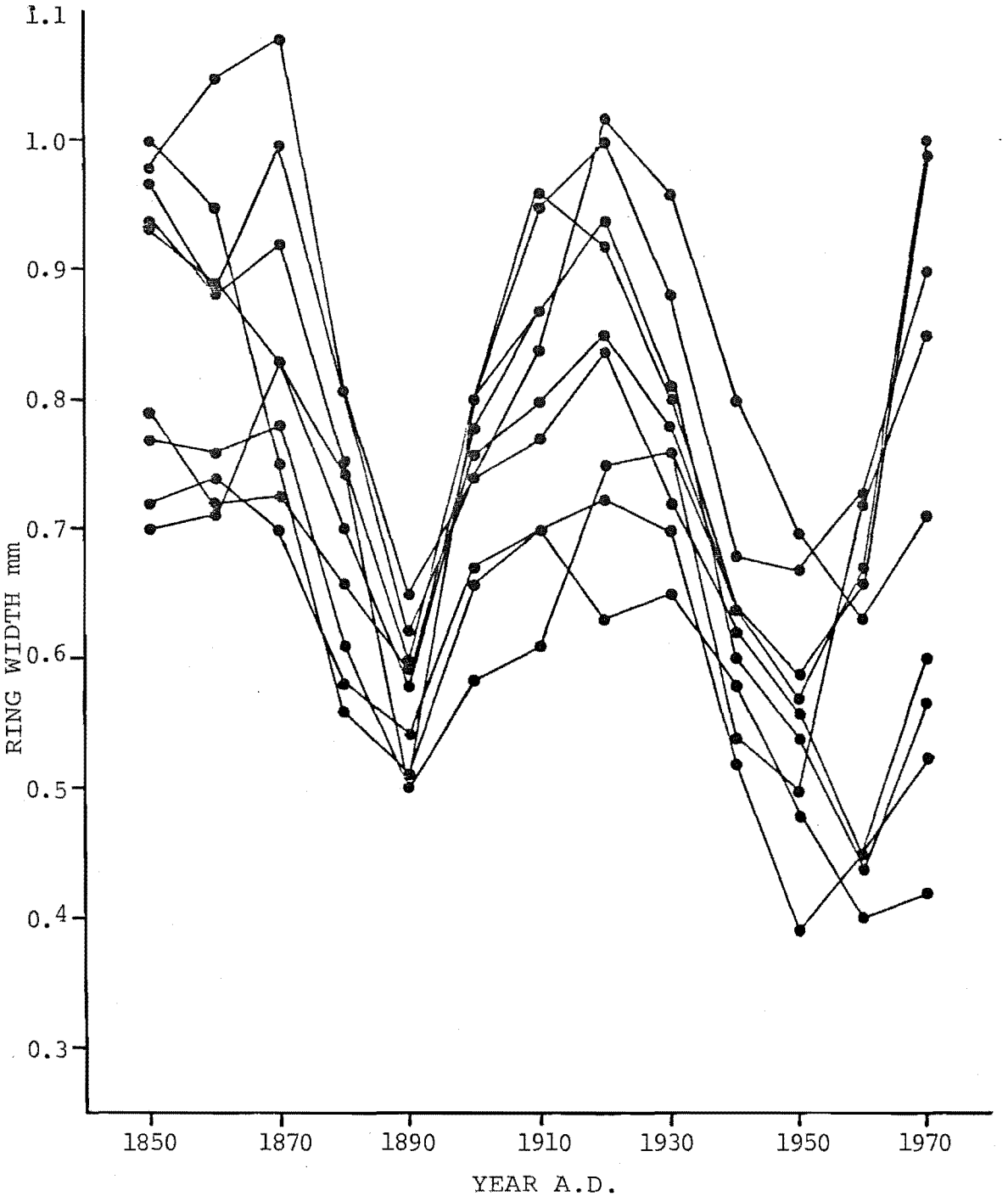


Figure 5.5a Twenty year means of radial growth of nine radii at different heights in a *Nothofagus solandri* tree.

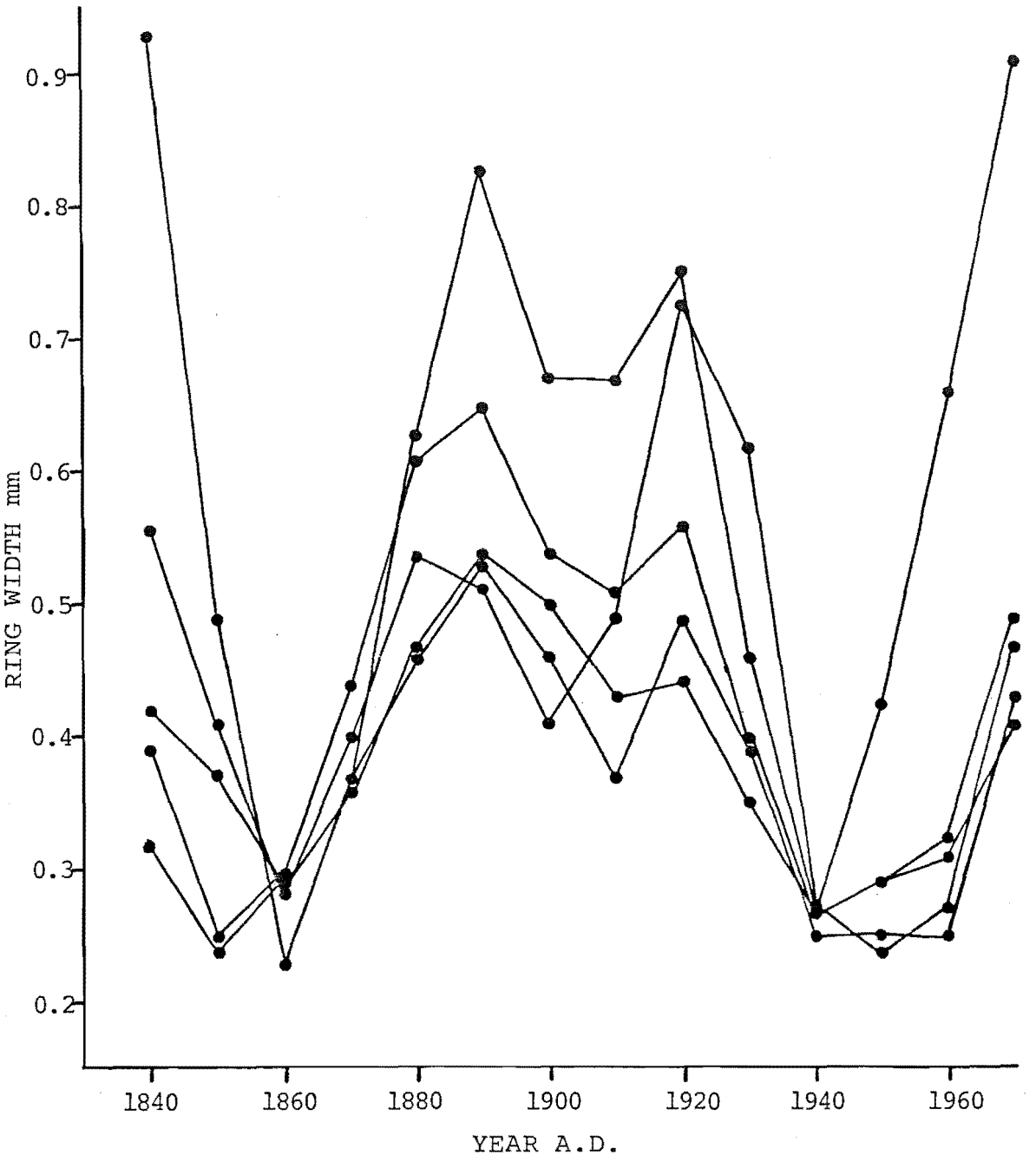
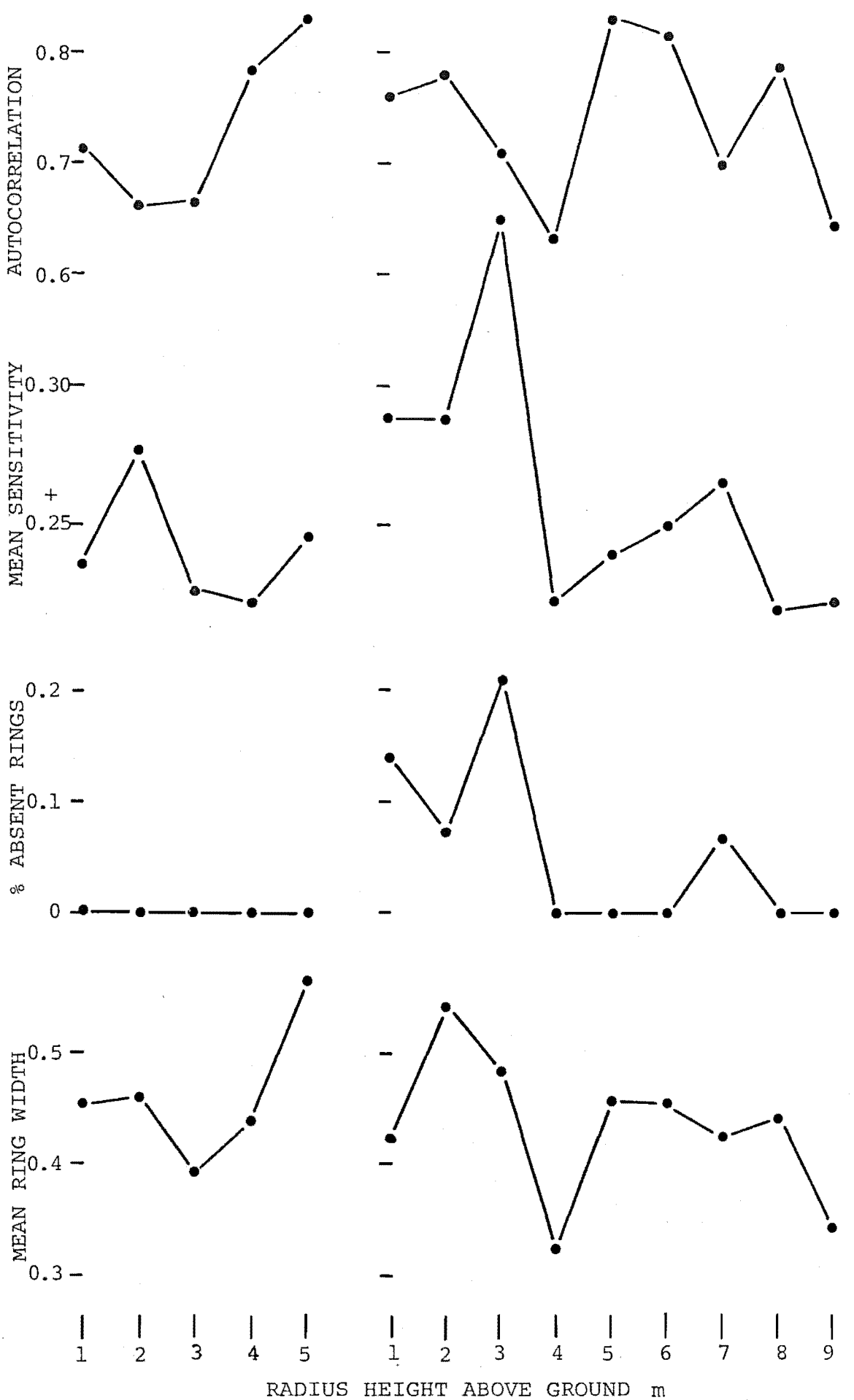


Figure 5.5b Twenty year means of radial growth of five radii at different heights in a *Libocedrus bidwillii* tree.

Figure 5.6 Variations in the statistics used to describe tree-ring width series from several series sampled at different heights in a *Libocedrus bidwillii* tree and a *Nothofagus solandri* tree.


Libocedrus bidwillii
Nothofagus solandri
AUTOCORRELATION
0.8
0.7
0.6
MEAN SENSITIVITY
0.30
+
0.25
% ABSENT RINGS
0.2
0.1
0
MEAN RING WIDTH
0.5
0.4
0.3
1 2 3 4 5
1 2 3 4 5 6 7 8 9
RADIUS HEIGHT ABOVE GROUND m

ring samples taken from near the base of the bole (e.g. at 1 m) not only have the longest records but also ring widths are most sensitive here and provide a reliable estimate of ring width variations throughout a large portion of the tree bole. However, Hughes and Milsom (1982) working with *Quercus petrea* trees from North Wales, found, in carrying out response function analyses on chronologies developed from two heights with sampled trees, that the amount of climatic variance explained was greater at 4 m than at 0.5 m. However, as was found here, mean sensitivity was greater at the lower height. Practical constraints on sampling will, however, largely confine sampling to the lower bole.

5.3.3 Measuring accuracy

One *Nothofagus solandri* tree was measured twice by myself and by two colleagues to check for measuring errors. Examination of the actual measurements showed the largest difference to be no more than 0.2 mm (measuring to 0.01 mm and with a mean ring width value of 1.77 mm) and the trends in the ring width between the four series were almost identical. Highly significant correlation coefficients ($P < 0.001$) with a mean of 0.98 (n=100, range 0.96 - 0.99) were obtained between the four measurements. Fritts (1976) presents a method for checking the reliability of measurements, involving the measuring of groups of 20 rings by several workers and calculating the difference between pairs of measurements. The differences are squared and the sum of the squares should not exceed 0.10 for arid site conifers and 0.23 for *Quercus alba*, a temperate forest tree of eastern North America. Sums equal to, or less than, the limit are within the acceptable measurement error. The cut off level has been determined through repeated measurements and its relevance to *Nothofagus solandri* is uncertain. However, values of 0.23, 0.22, 0.18, 0.14, 0.14 and 0.13 were obtained for two 20 year groups of rings between the original measurement and re-measurement by myself and two colleagues. These values are within the accepted limit for *Quercus alba*. Therefore measurement error is not considered a significant source of variation here.

5.4 ALTITUDINAL VARIATION

5.4.1 Introduction

A basic assumption made in this thesis is that the most sensitive chronologies, that is those with the best crossdating and strongest

correlation with climate (especially temperature), will be developed from trees growing close to the alpine timberline. The purpose of this section is to assess the validity of this assumption by comparing seven tree-ring chronologies that have been developed along an altitudinal transect from valley floor to timberline.

From Logos Hill (1422 m) in the Cass Valley (Fig. 5.7), a prominent ridge runs northeast for 2 km to the junction of the west and east branches of the Cass River (763 m). Monotypic *Nothofagus solandri* forests clothe the ridge almost to the top of Logos Hill, forming one of the highest timberlines in the area. The seven sites are located along this ridge at successive 100 m contours (Table 5.2, Fig. 5.7) and are referred to as site 1 (LGH1, the top site, 1400 m) to site 7 (LGH7, the bottom site, 800 m). At the two highest sites, many subalpine species (e.g. *Phyllocladus alpinus, Podocarpus nivalis, Coprosma* c.f. *pseudocuneata, Celmisia spectabilis, Gaultheria depressa* and *G.crassa)* are present in the forest. At site 1, *N.solandri* trees of multistemmed coppice growth form (Appendix 2) form a closed canopy at between 2 m and 3 m . Erect trees dominate at the other sites. Canopy height is about 8 m at site 2 and between 9 m and 14 m at the other sites. At the lower sites the forest canopy is closed except where windfalls have occurred. Although many mature trees are starting to die in these forests, possibly because of insect damage, the sampled trees were located in stands relatively free from such damage. At the five lower sites a discontinuous scrub layer is present, including *Coprosma linariifolia, C.microcarpa, C.rhamnoides, Aristotelia fruticosa, Gaultheria antipoda* and occasional *Cyathodes juniperina* with *N.solandri* seedlings and saplings. Some stunted *Podocarpus hallii* trees were noted near site 6. The scrub layer is most diverse at the lowest site and a deep layer of moss is present on the forest floor.

Changes in climate with increasing altitude are well documented. McCracken (1980) calculated a summer lapse rate of $0.85^{o}C/100$ m and a winter lapse rate of $0.42^{o}C/100$ m on the southeast side of the Craigieburn Range. Frosts are more frequent at higher altitudes and the snow cover lasts longer. Rainfall is greater at higher altitudes and vapour pressure deficits decline with increasing altitude.

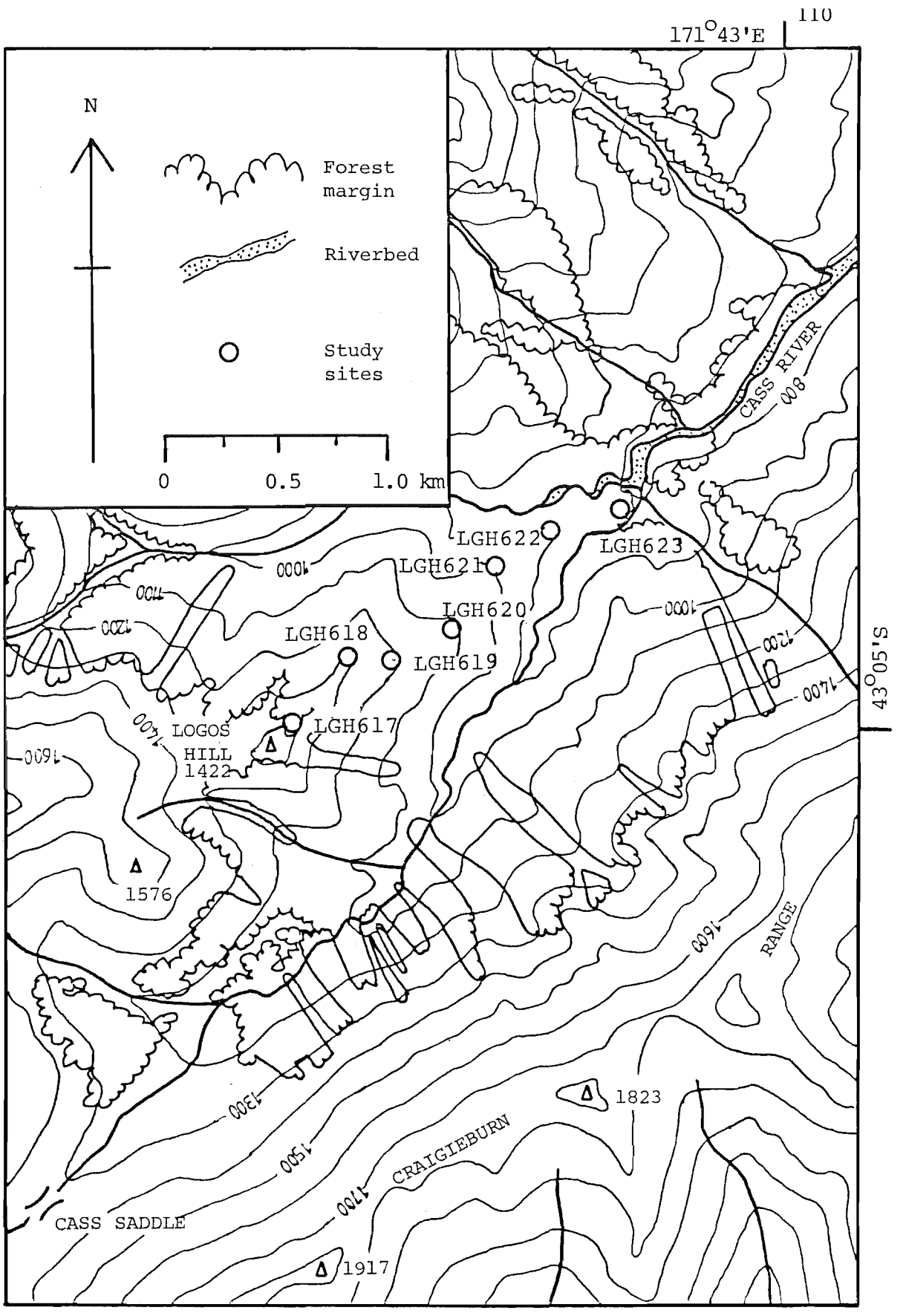


Figure 5.7 Location of the altitudinal transect study sites, Cass Valley, Craigieburn Range, Canterbury.

TABLE 5.2 Summary characteristics of the seven sites sampled along the altitudinal transect, Cass Valley.

Site	1	2	3	4	5	6	7
Altitude (m)	1400	1300	1200	1100	1000	900	800
Slope (^{o})	30	30	26	28	5	30	0
Aspect	N	E	SE	NE	SE	N	SE
Mean tree height (m)	2-3	8	10-12	9-11	10-12	9-12	10-14
Mean diameter at coring height (m)	0.18	0.32	0.39	0.34	0.32	0.37	0.35

5.4.2 Chronology characteristics

The seven sites were sampled using standard techniques (Chapter 4). Two cores per tree were taken from between 11 and 16 trees at each site, except site 1 where tree diameters were small (mean of 0.18 m) and 13 trees were sampled (one core per tree). Site details are summarised briefly in Table 5.2 and more fully in Appendix 4. The tree-ring samples were prepared, crossdated and standardised using the methods described in Chapter 4. The index values for the period common to all chronologies (1810-1979) are plotted in Fig. 5.8 and the complete chronologies presented in Appendix 4. The tree-ring statistics for each chronology are presented in Table 5.3 and for the shorter sample period in Table 5.4. Selected values are graphed in Fig. 5.9. The data are arranged in order of decreasing site altitude.

Site 1 is anomalous with respect to several of the statistics and is discussed separately. Except for the two lowest altitude sites, mean ring width decreases with increasing altitude (Fig. 5.9). Such a decrease is expected as the growing season is shorter at higher altitudes in the Craigieburn Range (Benecke and Havranek 1980a). However, J. Wardle (1970d) measured only slight differences in growth rate between 915 m and 1342 m elsewhere in the Craigieburn Range and considered differences in growth rates more pronounced between different forest associations than between populations at different altitudes. The low growth rates of trees at sites 6 and 7 could be due to site differences. Site 6 is on a well drained slope and the presence of *Podocarpus hallii* and *Cyathodes juniperina*, species tolerant of moderate soil moisture shortages, indicate that soil moisture could be limiting in some years. Site 7 is on level ground near the Cass River and water logging in some years may reduce growth rates. This site is also deeply shaded for much of the day and frosts were often observed during fieldwork on the adjacent river flats suggesting some interactions with temperature. The influence of climate on growth at these sites is discussed further in Chapter 8.

The percentage of locally absent rings increases with increasing altitude (Table 5.3) and is highest at site 2, 100 m below timberline. The value of 2.30% absent rings obtained at this site is the highest recorded for any chronology in this study; the mean value recorded for the 16 timberline *Nothofagus solandri* chronologies is 1.35%.

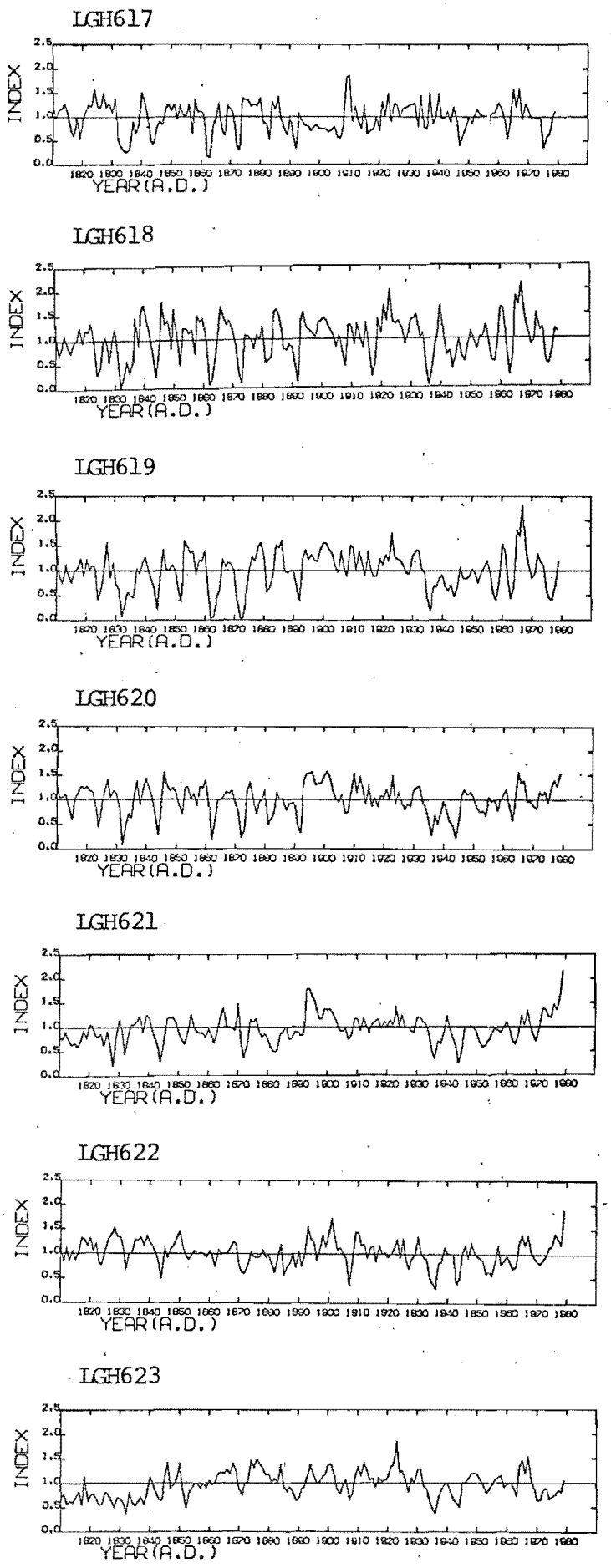


Figure 5.8 Standardised tree-ring chronologies for the seven *Nothofagus solandri* altitudinal transect sites.

TABLE 5.3 Chronology statistics for the seven chronologies from the altitudinal transect, Cass Valley.

Site	1	2	3	4	5	6	7
Number trees	13	11	16	11	14	11	7
Number radii	13	20	25	21	27	21	13
Period (A.D.)	1800-1979	1740-1979	1740-1979	1745-1979	1810-1979	1800-1979	1710-1979
Mean ring widths (mm)	0.87	0.66	1.08	0.95	1.19	0.90	0.82
% Absent rings	0.18	2.30	2.14	0.53	0.25	0.04	0.21
Standard deviation	0.32	0.42	0.38	0.31	0.29	0.26	0.33
Mean sensitivity	0.29	0.40	0.33	0.29	0.21	0.21	0.21
Autocorrelation	0.38	0.50	0.55	0.49	0.64	0.50	0.74

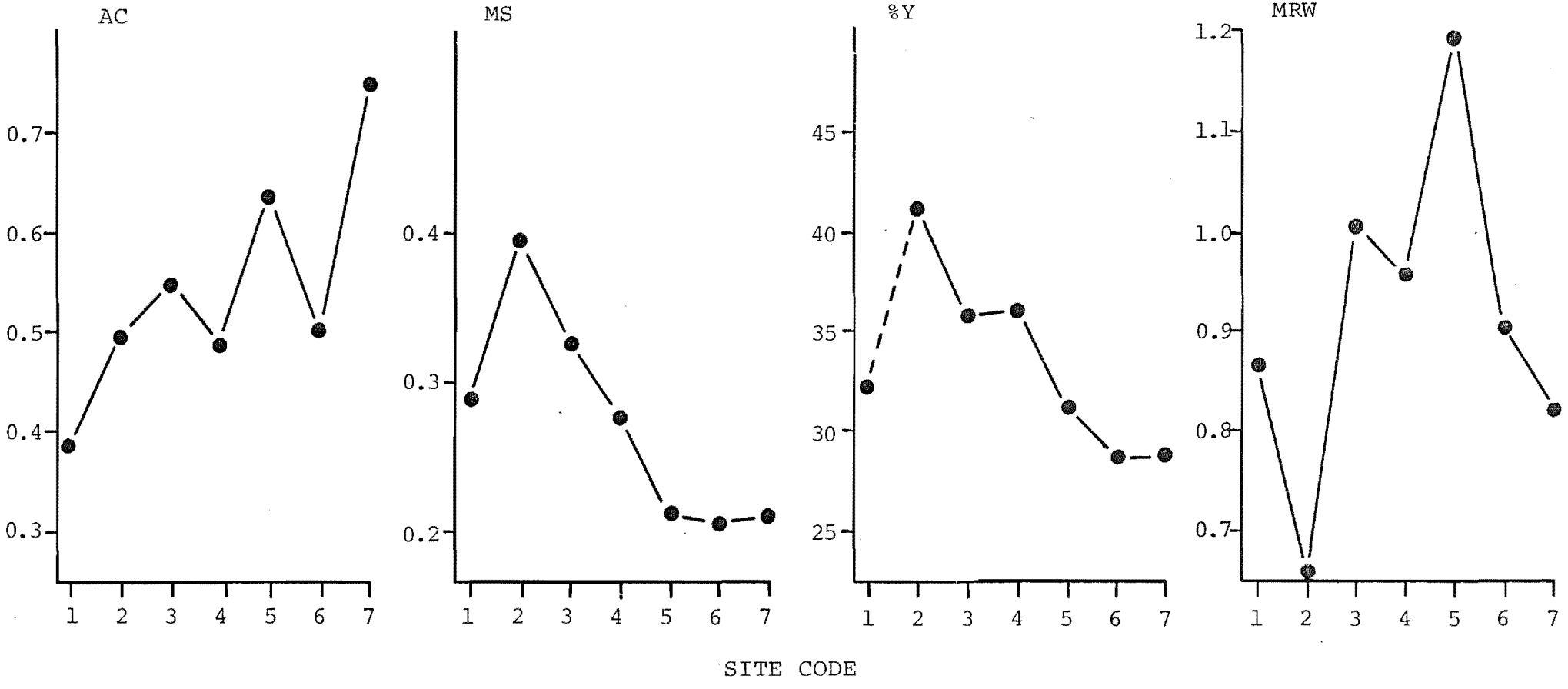


Figure 5.9 Variation in statistics used to describe tree-ring chronologies for seven *Nothofagus solandri* chronologies developed along an altitudinal transect in the Cass Valley, Craigieburn Range. AC - autocorrelation. MS - mean sensitivity. %Y - common variance in ANOVA. MRW - mean ring width in mm. Site code - 1, LGH617. 2, LGH618. 3, LGH619. 4, LGH620. 5, LGH621. 6, LGH622. 7. LGH623.

The highest altitude chronologies also have the most year to year variation (mean sensitivity, Fig. 5.9) reflecting an increased sensitivity to environmental variations. Standard deviations vary little with altitude, although the lowest site has the highest value. Autocorrelation increases with decreasing altitude. Autocorrelation measures the proportion of low frequency variance which is inversely related to high frequency variance (mean sensitivity). From these statistics it would seem that tree growth is becoming more sensitive to environmental fluctuations with increasing altitude.

The correlation analysis and analysis of variance results (Table 5.4) show a similar pattern. Variance common to all series in the chronology (%Y), and correlation values, increase with increasing altitude (Fig. 5.9) while variance due to differences between trees (%YxT/G) declines. This last statistic is lower at sites 6 and 7, probably due to site factors, as discussed earlier. With increasing altitude the tree-ring series from individual trees are becoming more similar and differences due to tree-specific effects are declining or are being cancelled out because of increasing environmental limitation.

Some of the differences in the signal-to-noise ratios (Table 5.4) are attributable to sample sizes (sites 4 and 7) as this ratio varies directly with the number of trees sampled (Graybill 1982). However, the decline in signal-to-noise ratio with decreasing altitude suggests that, compared to sites near timberline, much larger sample sizes are needed at lower altitudes to optimise the amount of climatic signal (%Y) relative to non-climatic "noise" (100-%Y).

Site 1 is anomalous in respect to several of the statistics, mainly because of stems are of young age and the site is located at the upper forest margin. In Chapter 2 it was suggested that growth started earlier at the timberline margin than in the closed forest below and this is evident in the increased ring width in Fig. 5.9. The numbers of absent rings are less and the mean sensitivity and correlation between all series (and inferred from this common variance) are lower (Fig. 5.9). This suggests that these trees are less sensitive to environmental variations than slower growing trees below timberline. The cluster analyses (presented in Chapter 6) separate this chronology out from others along the altitudinal transect, highlighting some of these differences. Damage, probably by frost, was observed in several

TABLE 5.4 Sample statistics for the seven chronologies from the altitudinal transect, Cass Valley.

Site	1	2	3	4	5	6	7
Number trees	13	9	9	7	9	10	5
Number radii	13	18	18	14	18	20	10
Period (A.D.)	1930-1979	1890-1979	1890-1979	1890-1979	1890-1979	1890-1979	1890-1979
% Y[1]	(32.00)[2]	41.30	35.85	36.08	31.30	28.78	28.82
% Y x T/G[1]	-	23.37	28.01	3.14	36.00	15.96	23.23
% other[1]	-	35.33	36.14	60.78	32.70	55.26	47.95
r within trees[3]	-	0.66	0.67	0.43	0.63	0.53	0.51
r between trees[3]	-	0.50	0.44	0.39	0.37	0.34	0.30
r all series[3]	0.40	0.51	0.45	0.39	0.38	0.35	0.32
S/N[4]	-	6.26	5.06	3.94	4.04	4.09	1.94

Notes: 1. Variance explained in ANOVA

2. Estimated using the assumption that common variance and correlation between all series are directly related (Fritts 1976, p.294).

3. Correlation analysis r values.

growth rings in trees at site 1 and usually involved distortion of vessel members. Distortion of cells (especially crushing) in timberline trees has previously been attributed to frost damage (LaMarche 1970). Frost rings were rare at other sites and the higher incidence is probably due to the longer growing season of these timberline margin trees and hence greater susceptibility to spring and autumn frosts. Frost damage common to several trees occurred early in the 1931-1932 growing season and late in the 1949-1950 growing season. Frost damaged rings, if sufficiently widespread in occurrence, can offer a useful crossdating parameter independent of ring width and can also give further environmental information (LaMarche 1970). Although sensitivity to environmental variation is lower at site 1 some information on past environments can be obtained by careful examination of frost damaged rings. However, such analysis will be limited by the usually young age of many coppice growth form stems.

The plotted chronologies from sites 5, 6 and 7 (Fig. 5.8) are less variable than those from sites 2, 3 and 4. Pronounced depressions in tree-ring indices in the 1830's, 1860's and 1890's prominent in the higher altitude chronologies are inconspicuous in the three lowest altitude chronologies. One of the cluster analyses (Chapter 6) groups sites 5, 6 and 7 together and separate from all other Craigieburn Range chronologies. The second cluster analysis clusters sites 4 and 5 with RBW and sites 6 and 7 with RTA. This relation with RTA may suggest some rainfall limitation at sites 6 and 7. Sites 2 and 3 cluster with ENT in both analyses. Site 1 clusters separately.

5.4.3 Discussion

In this section, data have been presented to illustrate the influence of altitude on the characteristics of the tree-ring chronologies. The pattern appears to be strongly related to the altitudinal temperature gradient. The mean lapse rate suggests a mean temperature difference of $4^{o}C$ between the upper and lower sites. The climatic correlation is investigated further in Section 8.5.

Much has been published on changes in forest structure and tree phenological patterns with increasing altitude (see review in Tranquillini 1979); reductions in tree height, tree growth rates and length of growing season are well documented. However, less is known about the nature of variation in the width of annual growth rings

at different altitudes. Studies by LaMarche (1974b) and Fritts and Shatz (1975) looked at chronology differences with respect to altitude but much of the observed pattern related to changes from semi-arid lower forest border sites to cold alpine timberline sites. Fritts et al. (1965) examined chronology variation from forest interior sites to semi-arid lower forest border sites. They found that the most sensitive trees were near the lower forest border. LaMarche (1974b) investigated a similar gradient; semi-arid lower forest border, forest interior, and alpine timberline. The most sensitive chronologies were at the upper and lower forest borders. His forest interior and alpine timberline sites are comparable with those discussed here and a similar increase in mean sensitivity and common variance (%Y) occurred. However, autocorrelation also increased with increasing altitude, but this may be related to a long leaf retention period (in *Pinus longaeva* and *P.aristata,* the species he studied), dampening the climatic response (LaMarche and Stockton 1974). Fritts and Shatz (1975) observed a decline in autocorrelation with increasing altitude but standard deviation and mean sensitivity values were highest between about 1800 m and 2300 m, being lower below and above this height. However, their results are difficult to interpret because their data came from a wide area; 102 chronologies located between 50^{o}N and 20^{o}N, and 120^{o}E and 140^{o}E.

From these different studies it is clear that as the forest border (either semi-arid lower border or alpine timberline) is approached, tree sensitivity and amount of common variance increases. Although climate does influence tree growth within the forest, its effect is most pronounced near environmental limits and in New Zealand *Nothofagus solandri* forests, the most sensitive trees are those close to, but not forming, the alpine timberline. It is here that one can expect the most climatic information to be retained in tree-ring chronologies.

5.5 MISCELLANEOUS CROSSDATING

5.5.1 *Nothofagus solandri*, inland Canterbury

Ring width patterns from trees sampled at the head of the Poulter River and in the Rakaia River Valley (Fig. 3.4) were successfully crossdated with the regional Craigieburn tree-ring pattern. The Rakaia Valley trees were young, probably having established after fire earlier this century and the crossdating was not strong. The mature trees near timberline in the upper Poulter exhibited a strong similarity

of ring width patterns to trees near timberline in the Craigieburn Range. Crossdating of these outlying sites would suggest that the ring width patterns characteristic of the Craigieburn Range can be found in timberline trees over a much larger area. This in turn would add weight to the suggestion of a regional climatic control of tree growth (see Chapter 6).

The forests of the upper Cass Valley are cut by a series of avalanche tracks (Fig. 5.10). Although not active every winter, avalanches have run these tracks many times in the last 100 years. By dating scars and eccentric growth (tension wood) in damaged *Nothofagus solandri* trees along the sides of these tracks, Conway (1977) has been able to develop chronologies of avalanche events for several tracks in the Craigieburn Range, including two in the upper Cass Valley (Cass 1 and Chronos).

During the present study, buried logs at the bottom of the Cass 6 avalanche track (Fig. 5.10) were sectioned. The three logs sectioned were buried under approximately 30 to 60 cm of alluvial material in the fan at the base of the track and had been exposed by river erosion. One log showed considerable evidence of decay but the other two still had bark present. One of the logs was successfully crossdated with the adjacent ENT and LGH2 tree-ring chronologies. From this, a date of 1967-1968 was obtained for the formation of the outside (most recent) growth ring. This was the most recent growth ring found around the circumference and gives a minimum date for tree death.

The winter of 1968 was characterised by deep snow accumulation in the Craigieburn Range and many avalanches were known to have occurred in most of the tracks in the upper Cass Valley. It would seem probable that the dated log was deposited during one of these events. Many avalanches only run in the centre of these tracks (e.g. during the 1982 winter) so the presence of an old log (270 to 280 years at 1.5 m) would suggest that the avalanche concerned was either of considerable size or was confined to one side of the track, either way damaging mature forest. Further research is needed to confirm the occurrence of an avalanche event and its extent during the 1968 winter in the Cass 6 track. However, the successful cross-dating of this log does suggest a further line of evidence that can be used to date past avalanche events.

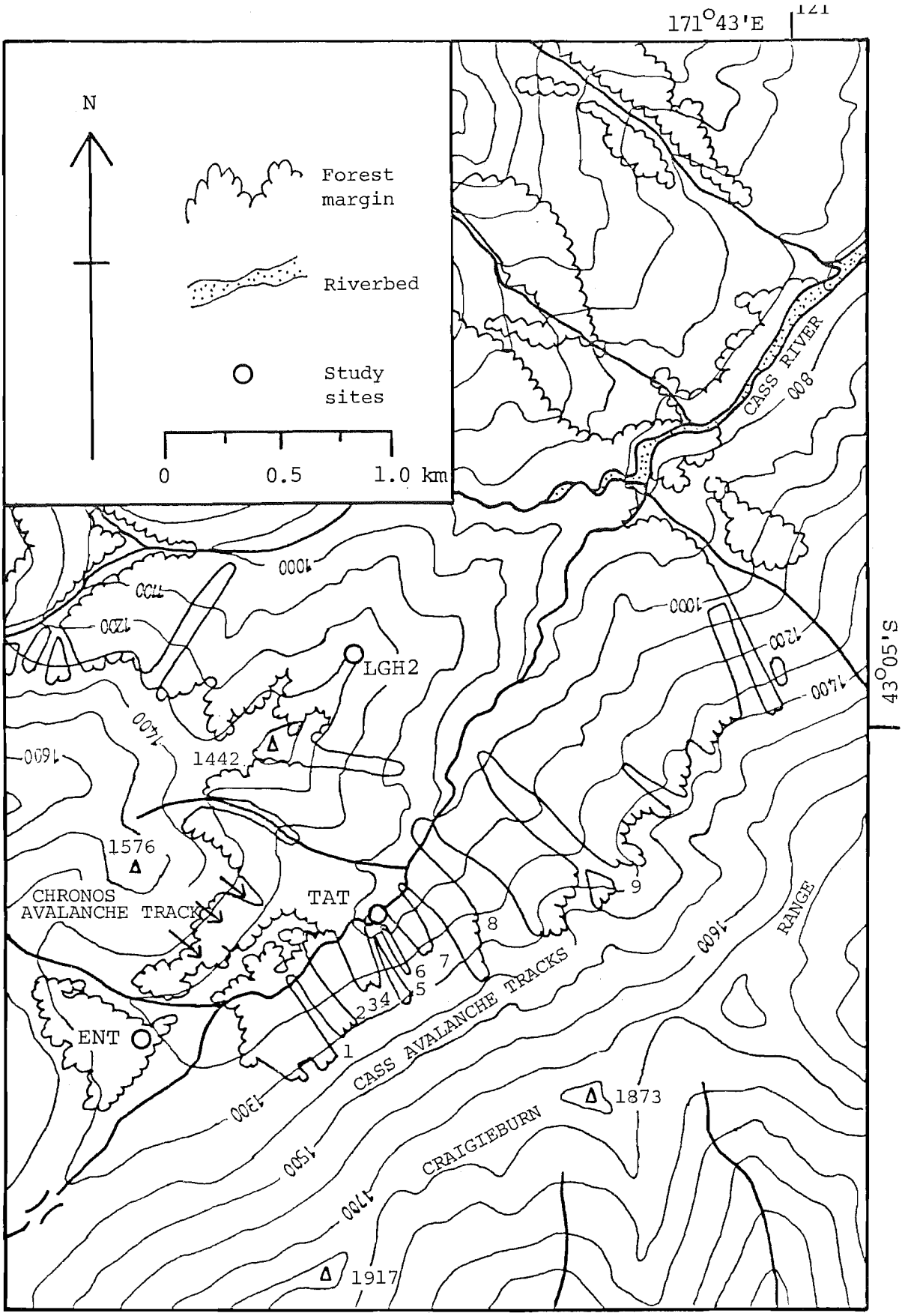


Figure 5.10 Location of site (TAT) in the Cass Valley, Craigieburn Range, from which a buried *Nothofagus solandri* log was crossdated with the ENT and LGH2 tree-ring chronologies.

5.5.2 *Libocedrus bidwillii*, Banks Peninsula

Dunwiddie (1979) developed a *Libocedrus bidwillii* chronology (ARM) using dead trees from Armstrong Reserve near Akaroa, Banks Peninsula (Fig. 5.11). At the time of his study, no live adult *L.bidwillii* trees were known on Banks Peninsula, although seedlings are present at some sites (P. Wardle 1978). Dating was established by crossdating with sites elsewhere in New Zealand (e.g. Mount Egmont and Mount Cargill). Further details of this chronology are given by LaMarche et al. (1979c).

Subsequent to Dunwiddie's study, a living adult *Libocedrus bidwillii* tree has been located on Banks Peninsula (Molloy 1978), near Trig KK (NZMS1 S84 142337, 686 m a.s.l.), 22 km to the north-west of the ARM site. At the start of the present study, two cores were extracted from this tree and successfully crossdated with the ARM chronology (Fig. 5.12) and confirm the dating proposed by Dunwiddie (1979). These measurements were standardised and incorporated into the ARM chronology by multiplying the value for each year by the number of observations, adding in the two new measurements, and dividing by the number of observations plus two. The recalculated chronology is presented in Appendix 4.

5.5.3 *Nothofagus* spp. Lake Te Anau

Five *Nothofagus menziesii* and five *N.solandri* trees were sampled in tall closed forest on the shore of Lake Te Anau. These trees could not be crossdated either with each other or with timber-line trees in the nearby Takahe Valley. Some narrow rings were common to more than one tree but could be due to either environmental limitation or to flowering and seed set (see discussion in Chapter 6). However, these rings were rare and not present in all trees and were hence of no value for crossdating.

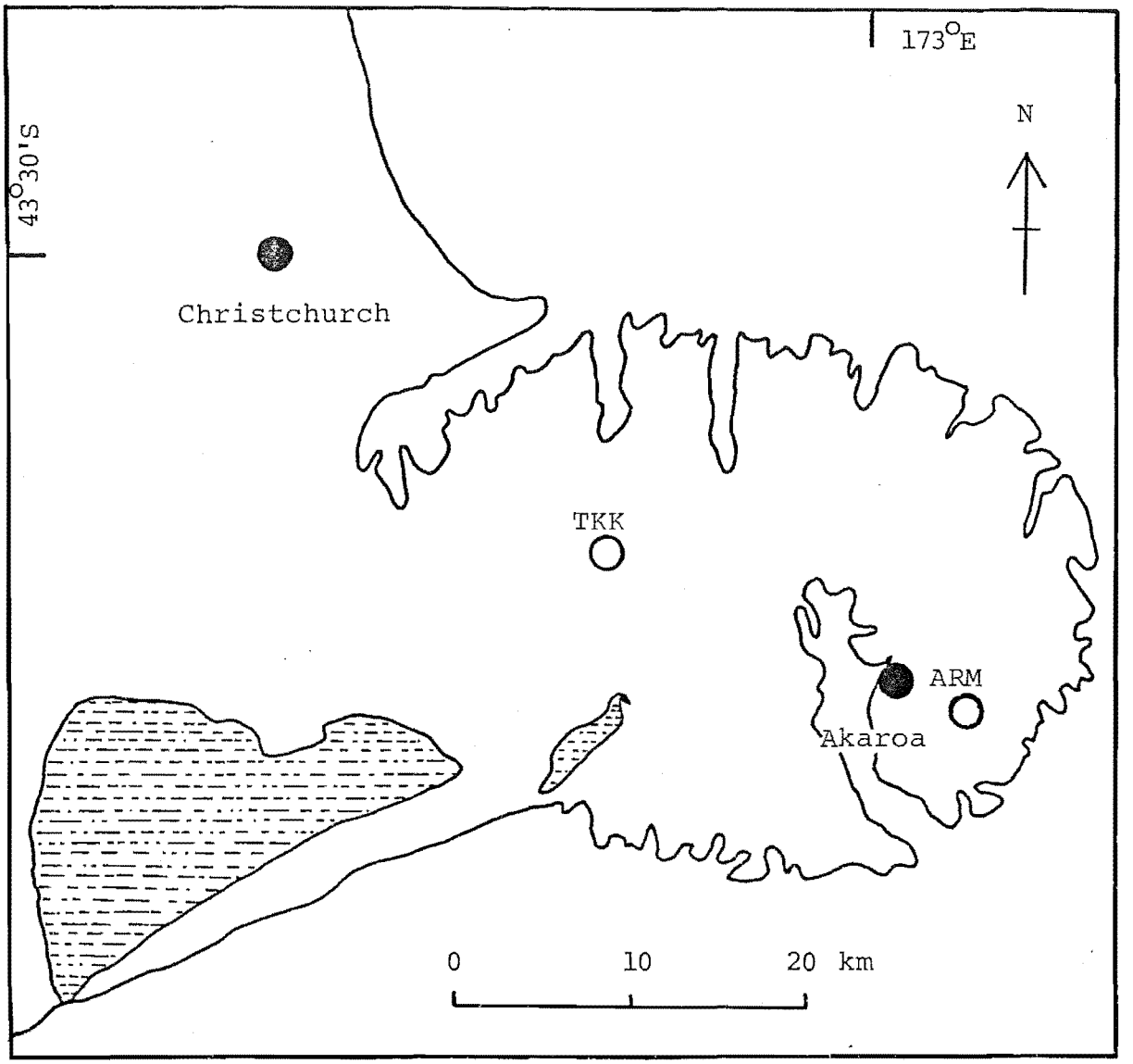


Figure 5.11 Loacation of the ARM and TKK tree-ring sites, Banks Peninsula, Canterbury.

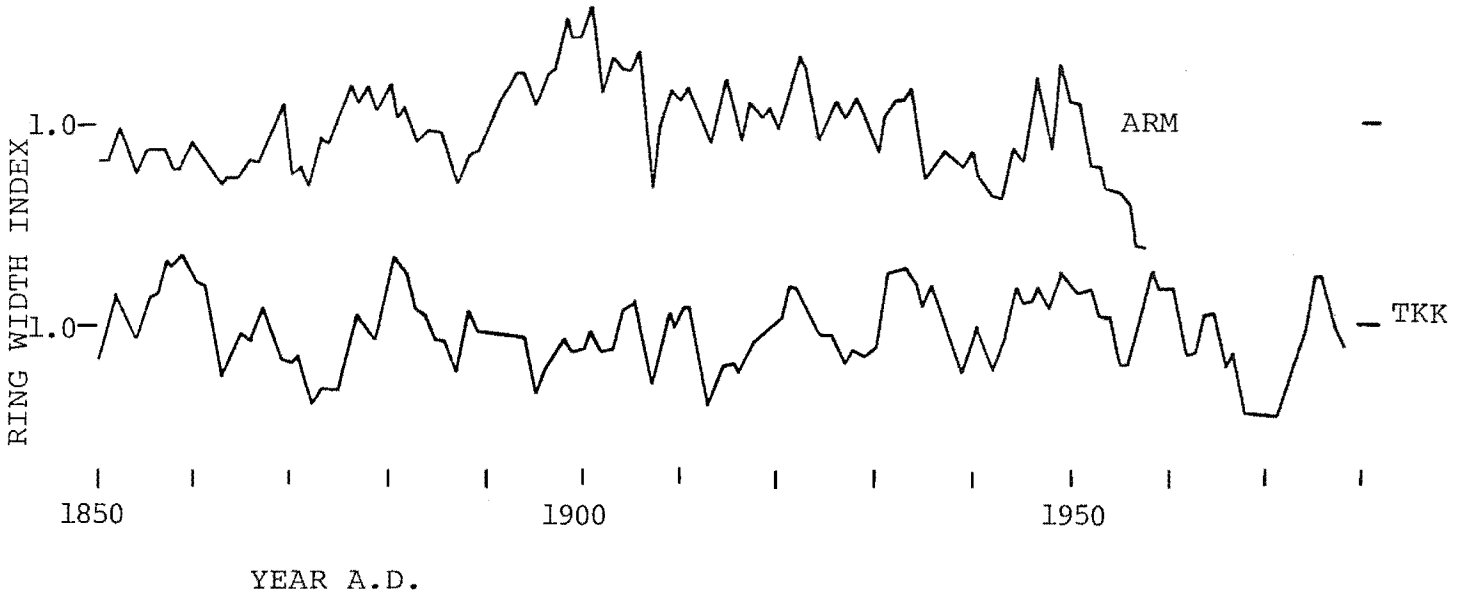


Figure 5.12 Ring width variations in the *Libocedrus bidwillii* ARM site chronology and in the combined series from two radii extracted from one *L.bidwillii* tree at the TKK site.

CHAPTER SIX

CHRONOLOGY STATISTICS

6.1 INTRODUCTION

Thirty-three tree-ring chronologies were developed. As a base-line for comparison a pseudo-chronology was also developed, using 12 series of 200-year random numbers. The chronologies are listed and plotted and descriptive statistics tabulated in Appendix 4. The descriptive statistics are divided into two sets; chronology statistics which describe the properties of the mean chronology and sample statistics which are based on the analysis of a subset of the mean chronology. The subset analysed consists of trees with two radii each for a common time period. These chronologies and their statistics are discussed and compared in this chapter.

In selecting tree-ring chronologies for dendroclimatic analysis, Fritts and Shatz (1975) have suggested four statistics which they consider useful for characterising chronologies; mean sensitivity, autocorrelation, standard deviation and common variance (%Y in ANOVA). For each of these statistics and also for variance due to differences between trees (%YxT/G), the mean value, standard deviation, 50% theoretical population limits (±0.67 standard deviations) and 95% theoretical population limits (±2 standard deviations) were calculated and used to characterise chronologies. A further statistic, the signal-to-noise ratio (S/N), is considered useful in evaluating chronologies (DeWitt and Ames 1978, Graybill 1982) and was used here.

Two types of statistical analysis were used to assist in interpreting inter- and intra-specific variation between chronologies. Firstly, Pearson product-moment correlation coefficients were calculated between all chronologies (except WFT) for the period 1840-1978. The SPSS statistical package (Nie et al. 1975) was used and the results are presented in Fig. 6.1. Secondly, two cluster analyses were used to group the chronologies for the same time period. The first was performed using the P1M program in the BMDP statistical package (Dixon 1981). Similarity was calculated as the arc cosine of the correlation coefficient between two chronologies and linkage was determined as the average similarity between chronologies. Average similarity is the

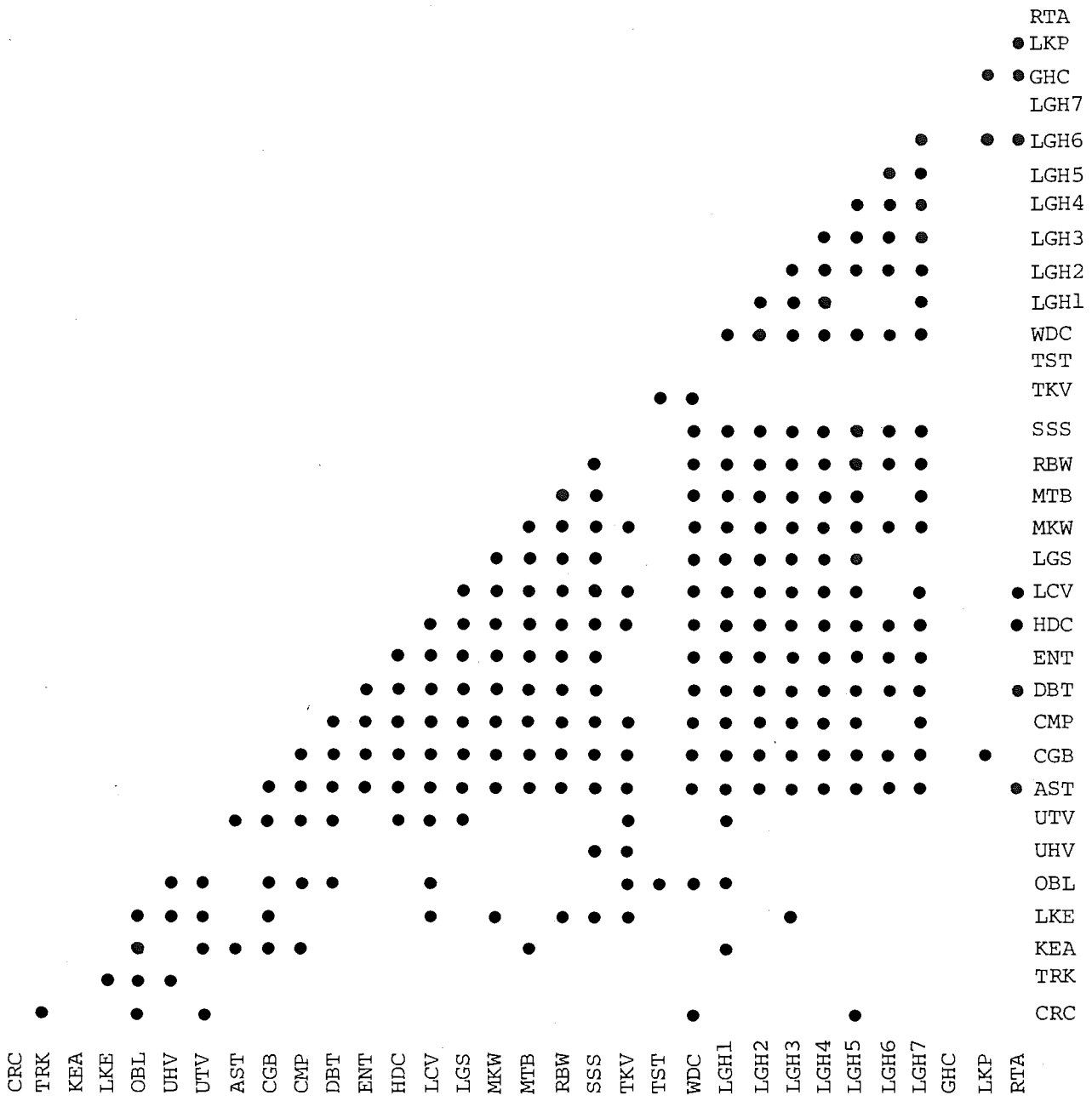


Figure 6.1 Results of correlation analysis between all tree-ring chronologies developed, except WFT, for the period 1840 to 1978. All correlations are significant at the 95% level if marked.

arithmetic average of the similarity using all possible pairings of chronologies between clusters. The resultant cluster is presented in Fig. 6.2. The second cluster analysis was performed using programs in the MINT numerical taxonomy system (Ward 1982). Average euclidian distance was used to determine the similarity between chronologies and the unweighted pair-group method using arithmetic averages was used to link chronologies in the clusters. The resultant cluster is presented in Fig. 6.3. Although much debate has centred around the relative merits of different clustering methods (e.g. Williams and Lambert 1966) these are not discussed here as clustering was used only in a descriptive sense (c.f. as a basis for classification). In both statistical packages, several different clustering options were available and several were attempted here. The two methods discussed above produced the "best" (i.e. most biologically logical) and most similar clusters.

6.2 *LIBOCEDRUS BIDWILLII*

Two *Libocedrus bidwillii* chronologies (CRC and TRK) were developed from subalpine forest trees in Westland. To improve replication, tree-ring series from two adjacent sites (DNG and TRK) were combined to form the TRK chronology. The chronologies are listed and plotted and descriptive statistics presented in Appendix 4. The descriptive statistics are summarised in Tables 6.1 and 6.2.

The pattern of narrow and wide rings are similar between the two chronologies and for the period 1840-1978 the correlation coefficient is highly significant ($r=0.69$, $P<0.001$). The two chronologies cluster together in both cluster analyses suggesting that they are more similar to each other than to other chronologies. The observation that few patterns of narrow and wide growth rings were common between these chronologies and those developed with *Nothofagus* spp. confirms this.

The two chronologies were the longest developed here (CRC - 519 years, TRK - 453 years). Although the number of trees used is adequate (15 and 20), replication is poor and in the TRK chronology, two radii per tree were measured in only six trees. However, the filtered chronologies (Appendix 4) are similar suggesting that despite poor replication, considerable common variance, both high frequency and medium-low frequency, is present in these chronologies.

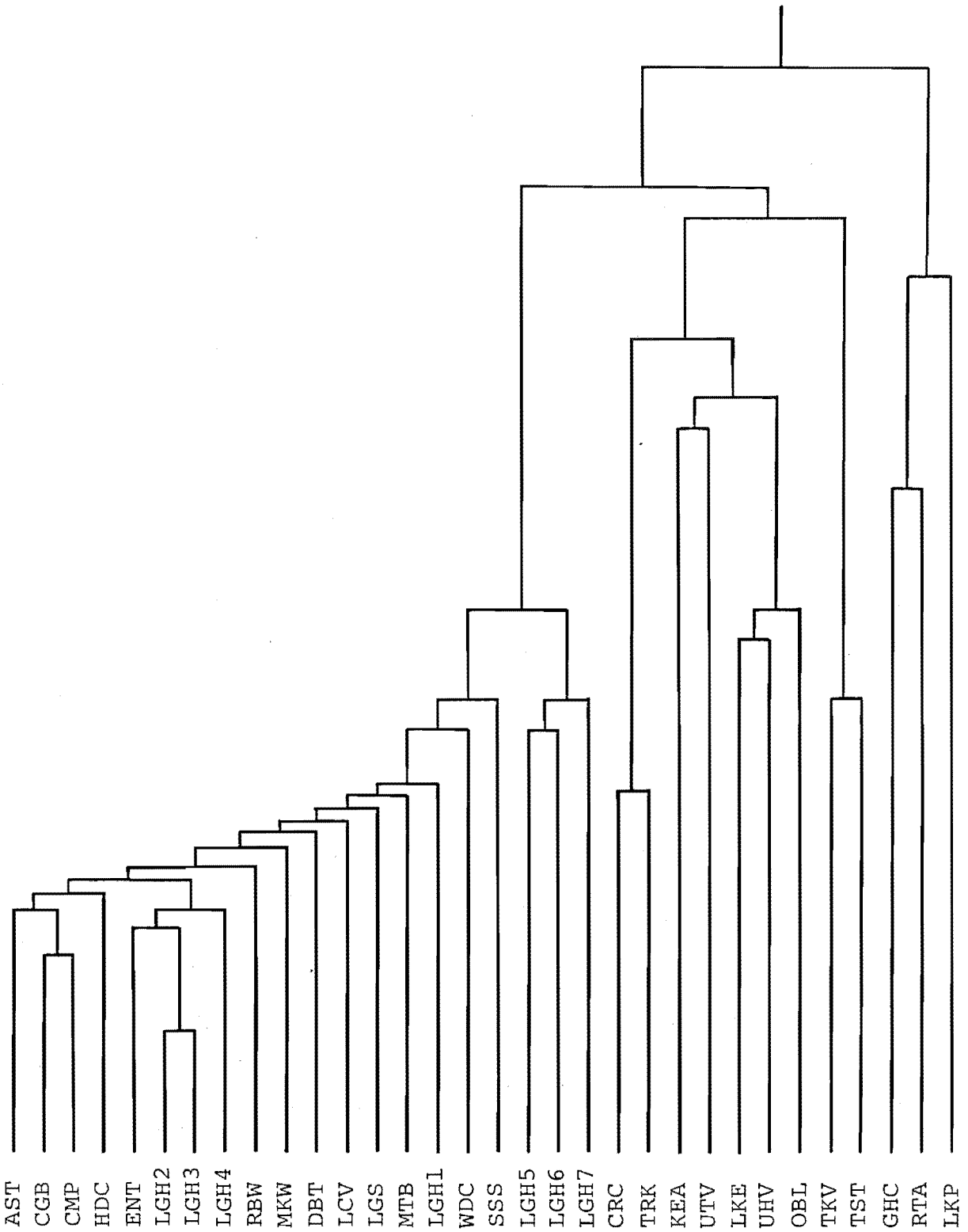


Figure 6.2 Cluster analysis dendrogram of the tree-ring chronologies for the period 1840-1978. Developed using BMDP statistical package.

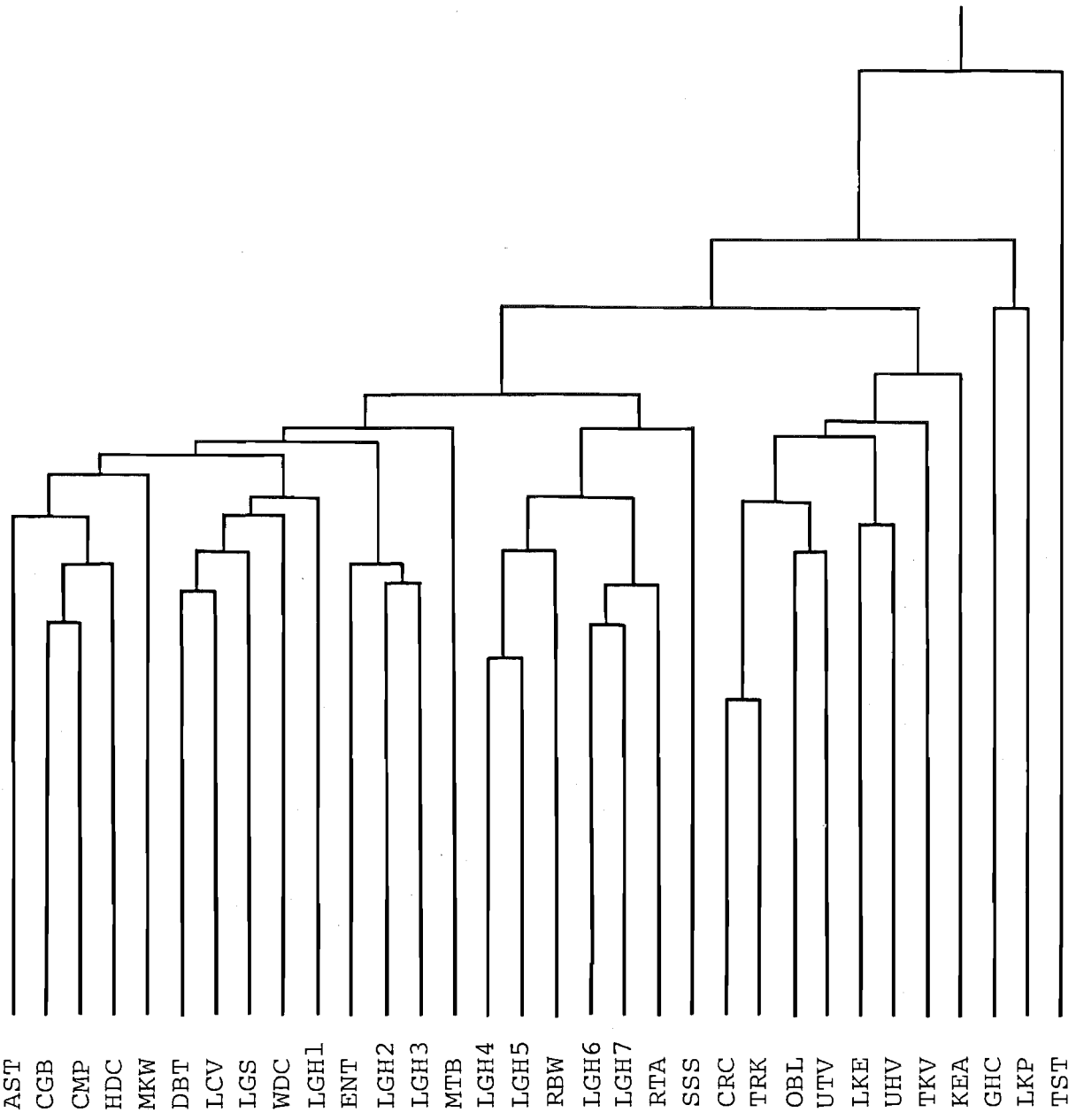


Figure 6.3 Cluster analysis dendrogram of the tree-ring chronologies for the period 1840-1978. Developed using the MINT statistical package.

TABLE 6.1 *Libocedrus bidwillii* chronology statistics.

Code	No.trees	No.radii	Period (A.D.)	AC[1]	MS[2]	SD[3]	%Abs[4]	MRW[3]
CRC601	15	25	1460-1978	0.71	0.16	0.24	0.21	0.67
TRK602	20	27	1526-1978	0.58	0.17	0.31	0.24	0.52
LaMarche et al. (1979c)		mean		0.69	0.15	0.24	0.44	0.80
(9 chronologies)		range		0.50-0.87	0.12-0.17	0.18-0.32	0-2.17	0.56-1.06
Combined data		mean		0.68	0.15	0.25	0.40	0.76
(11 chronologies)		standard deviation		0.11	0.02	0.05	0.64	0.19
		± 50% limits		0.07	0.01	0.03	-	-
		± 95% limits		0.22	0.04	0.10	-	-

Notes: 1. Autocorrelation
2. Mean sensitivity
3. Standard deviation
4. Per cent absent rings
5. Mean ring width (mm)

TABLE 6.2 *Libocedrus bidwillii* sample statistics.

Code	No.trees[1]	Period (A.D.)	%Y[3]	ANOVA[2] %YxT/G[4]	% other	S/N[5]	Correlation Analysis[6] r all series	r within trees	r among trees
CRC601	10	1849-1978	27	33	40	3.70	0.30	0.58	0.29
TRK602	6	1897-1964	17	17	66	1.23	0.20	0.35	0.18
LaMarche et al. (1979c)		mean	28	28	46	4.04	0.31	0.55	0.29
(9 chronologies)		range	18-38	9-39	33-62	2.20-6.13	0.22-0.40	0.41-0.66	0.20-0.39
Combined data		mean	27	26	47	3.76	0.30	0.54	0.28
(11 chronologies)		standard deviation	6	10	11	1.27	0.06	0.10	0.06
		± 50% limits	4	7	-	0.85	-	-	-
		± 95% limits	12	20	-	2.54	-	-	-

Notes:
1. Two cores per tree
2. Values given to two significant figures only, so as to be comparable with the data in LaMarche et al. (1979c).
3. Common variance
4. Differences between trees
5. Signal-to-noise ratio
6. Mean correlation coefficients

The chronology and sample statistics obtained are similar to those presented by LaMarche et al. (1979c) for other *Libocedrus bidwillii* chronologies (Tables 6.1 and 6.2). These two groups of chronologies are considered together, giving a set of 11 chronologies. Autocorrelation values are high and mean sensitivities and standard deviations low. These statistics are consistent between the different chronologies. Per cent absent rings varies from 0 to 2.17% but is less than 0.30% in eight of the chronologies (including those developed here).

Low mean sensitivity and standard deviation values and high autocorrelation values can be explained, in part, by the retention of photosynthetic tissue. Needle retention is important in modifying the climatic response of *Pinus longaeva* trees at alpine timberlines in Western North America (LaMarche and Stockton 1974). Needle production is directly related to summer temperature and needles are retained for 10 to 15 years or more. The total needle area available for photosynthesis at any one time therefore reflects the climatic conditions influencing needle production during preceding years and consequently these tree-ring chronologies have high autocorrelation values. *Libocedrus bidwillii* also retains its leaves for several years (P. Wardle 1963b, suggests six to eight years but it could be longer). It would therefore seem likely that the long period of photosynthetic tissue retention by *L.bidwillii* trees could also considerably modify ("dampen") the response of this species to climate, with high autocorrelation values reflecting this. Autocorrelation values for *L.bidwillii* are amongst the highest recorded, being comparable with *Austrocedrus chilensis* and *Araucaria araucana* in South America (LaMarche et al. 1979a,b) and *Arthrotaxis* spp. in Tasmania (LaMarche et al. 1979d).

For the sample period, low common variance (%Y) and low variance due to tree differences (%YxT/G) are usual, while variance between the individual radii (%YxCxT/G) is high. The ratio of these three variance sources is approximately 1:1:2. Signal-to-noise ratios, which give an indication of the amount of non-climatic "noise" relative to the amount of climatic signal, help exemplify the importance of these different sources of variance. It has been suggested that a signal-to-noise ratio of 15 is desirable to maximise the climatic signal in tree-ring chronologies (DeWitt and Ames 1978). A mean signal-to-noise ratio of 3.76 for the *Libocedrus bidwillii* chronologies is low and with a mean common variance of 27%, at least 41 *L.bidwillii* trees would need to be sampled to increase this to 15. Low cross-correlation values are a

further measure of the relative similarity between different groupings of radii.

Much of the "noise" in these chronologies can be related to the regeneration strategies of this species. *Libocedrus bidwillii* has an intermittent regeneration mode (Clayton-Greene 1977, Veblen and Stewart, 1982, Appendix 1) and in any stand, several generations of trees can be present, often in even-aged groups. Ogden (1982) has suggested that interference within and between different generations adds considerably to "noise" in chronologies. Large sample sizes would be necessary to overcome this problem in *L.bidwillii*. A further portion of this non-climatic variance is due to differences between radii in the same tree and is probably in part related to irregular shaped tree canopies (e.g. flag-form) resulting in an uneven distribution of food and growth-controlling substances within the tree.

Despite the large amount of "noise" in these chronologies, considerable common variance is present and can be seen in both low and high frequency variations in the tree-ring indices. The two chronologies developed here (CRC and TRK) are very similar at both frequencies. These similarities, especially at low frequencies, suggest that tree growth at these sites (1.5 km apart) is being influenced by some factor or factors external to the sites themselves. Several similarities also exist between all of the *Libocedrus bidwillii* chronologies with synchronous narrow rings prominent in most chronologies in several years (e.g. A.D. 1566, 1582, 1652, 1720, 1833, 1935). Some periods of above or below normal growth are also common (e.g. depressed growth in the 1570's and 1580's and late nineteenth century). These similarities between widely spaced chronologies developed from throughout New Zealand strongly suggest a regional climatic control of tree growth. This question is pursued further in Part III of this thesis.

6.3 *NOTHOFAGUS MENZIESII*

Nothofagus menziesii was the only species investigated here for which chronologies have not previously been developed. Dunwiddie (1979) mentions that limited collections of *N.menziesii* cores from Mount Cargill could be crossdated. Five chronologies were developed (KEA, LKE, OBL, UHV, UTV) and these are presented with associated statistics in Appendix 4. Chronology and sample statistics are summarised in Tables 6.3 and 6.4.

TABLE 6.3 *Nothofagus menziesii* chronology statistics.

Code	No.trees	No.radii	Period (A.D.)	AC[1]	MS[2]	SD[3]	%Abs[4]	MRW[5]
KEA637	8	15	1580-1980	0.18	0.37	0.34	0.74	0.93
LKE636	10	19	1676-1980	0.43	0.35	0.38	0.49	1.23
OBL610	12	20	1584-1980	0.43	0.31	0.37	0.34	0.94
UHV635	9	18	1710-1980	0.50	0.24	0.31	0.19	1.08
UTV611	10	16	1622-1979	0.56	0.30	0.38	0.33	1.51
Combined data		mean		0.42	0.31	0.36	0.42	1.14
(5 chronologies)		standard deviation		0.14	0.05	0.03	0.21	0.24
		± 50% limits		0.10	0.03	0.02	-	-
		± 95% limits		0.28	0.10	0.06	-	-

Notes: See Table 6.1

TABLE 6.4 *Nothofagus menziesii* sample statistics.

Code	No.trees[1]	Period (A.D.)	%Y[2]	ANOVA %YxT/G[3]	% other	S/N[4]	Correlation Analysis[5] r all series	r within trees	r among trees
KEA637	5	1881-1980	28.43	24.32	47.25	1.94	0.33	0.56	0.30
LKE636	6	1861-1980	30.64	21.83	47.53	2.70	0.34	0.52	0.33
OBL610	5	1863-1979	33.78	13.38	52.84	2.58	0.37	0.51	0.35
UHV635	7	1882-1980	37.61	16.61	45.78	4.29	0.40	0.53	0.39
UTV611	6	1877-1961	24.96	30.46	44.58	2.00	0.29	0.56	0.26
Combined data		mean	31.08	21.32	47.60	2.70	0.35	0.51	0.34
(5 chronologies)		standard deviation	4.86	6.67	3.16	0.95	0.03	0.06	0.03
		± 50% limits	3.26	4.47	-	0.64	-	-	-
		± 95% limits	9.72	13.34	-	1.90	-	-	-

Notes:
1. Two cores per tree
2. Common variance
3. Differences between trees
4. Signal-to-noise ratio
5. Mean correlation coefficients

Correlation coefficients calculated between the ten different chronology combinations gave a mean value of 0.39. Seven of the ten are significant at the 99.9% level ($P < 0.001$) and the other three are significant at the 95% level ($P < 0.05$). Two of this latter group involve the KEA site which lies 200 km to the north of the other sites. The two cluster analyses group the chronologies together, but in different combinations. Significantly, one of the analyses (Fig. 6.3) places the KEA site farthest from the others. In both the cluster analyses the *Nothofagus menziesii* chronologies are quite clearly separated from the Craigieburn Range *N.solandri* chronologies but are grouped with the Fiordland *N.solandri* chronologies and with the two *Libocedrus bidwillii* chronologies. This grouping quite possibly has a climatic basis as these sites are all close to the main divide of the Southern Alps, while the Craigieburn Range sites are sited well to the east.

As a group, the *Nothofagus menziesii* chronologies are consistent in their statistics, except for the KEA chronology (Tables 6.3 and 6.4). The KEA chronology has an unusually low autocorrelation value. *N.menziesii* trees can live for more than 400 years. Long chronologies were developed; the longest two, KEA and OBL, extend back to 1580 and 1584 A.D. respectively. Mean ring width is about average but as mentioned in Chapter 5, growth rates are exceptionally slow in some timberline trees. The percentage absent rings is low, ranging from 0.19 to 0.74% in the measured trees. Autocorrelation values are low to moderate with a mean of 0.42. If the unusually low value of 0.18 for the KEA site is ignored, this increases to 0.48. Mean sensitivity and standard deviation values are high.

The analysis of variance results are similar between the five chronologies and common variance (%Y) ranges from 25 to 38% with a mean of 31%. Differences between trees are low, and at one site (OBL) only 13% of the variance is due to this. Low between tree variance would suggest that the sampled sites were fairly homogeneous. Despite the low between tree variance, considerable "noise" still remains in the chronologies and signal-to-noise ratios are low. To maximise this ratio, at least 33 trees would need to be sampled for each chronology. Correlation coefficients between trees are higher than between radii within trees emphasising that considerable "noise" still remains in these chronologies.

Nothofagus menziesii trees would seem very suitable for dendroclimatic analysis, having high mean sensitivity and standard deviation values and low autocorrelation values. However, sample sizes need to be increased to maximise the climatic signal.

6.4 *NOTHOFAGUS SOLANDRI*

6.4.1 Bluff site chronology statistics

Three *Nothofagus solandri* chronologies (GHC, LKP, RTA), initially presented elsewhere (Norton 1979, Aston 1982), were re-analysed here. These chronologies were developed from trees growing in low altitude bluff sites and form a distinct group of tree-ring chronologies. To ensure a standard method of chronology development, the original ring width measurements were re-standardised and the chronologies presented in Appendix 4 differ slightly from the earlier versions. The chronology and sample statistics are presented in Appendix 4 and summarised in Table 6.5.

Although all three chronologies readily crossdate with each other, correlation coefficients are low (0.27, 0.32, 0.44: $P < 0.001$) for the period 1840-1978. These low values could be due to little similarity in the ring width patterns between years of good crossdating and to site differences (especially differences in altitude and rainfall). One of the cluster analyses groups all three chronologies together and separate from all others (Fig. 6.2). The second analysis (Fig. 6.3) groups GHC and LKP together, but places RTA with the low altitude Logos Hill altitude transect sites, LGH6 and LGH7 (Chapter 5). This second cluster could indicate a similarity between RTA and the LGH6 and LGH7 chronologies, rather than a dissimilarity with the GHC and LKP chronologies.

Tree ages at the three sites are young and the oldest tree measured is only about 200 years. This is considerably less than was obtained for *Nothofagus solandri* trees growing near the alpine timberline, where many trees are over 200 years old. The nature of the sites, with the possibility of frequent rockfalls, probably results in a limited tree life and therefore reduces the likelihood of long chronologies being developed at these sites. Tree growth rates are fast, on average, compared with trees from other chronologies developed here and elsewhere in New Zealand (LaMarche et al. 1979c). Autocorrelation values are low to

TABLE 6.5 *Nothofagus solandri* (bluff sites) chronology and sample statistics.

Code	No.trees	No.radii	Period (A.D.)	AC[1]	MS[2]	SD[3]	%Abs[4]	MRW[5]
GHC607	12	20	1795-1980	0.44	0.32	0.37	0.23	1.41
LKP609	6	11	1833-1978	0.56	0.25	0.36	0	1.00
RTA606	12	21	1787-1980	0.26	0.20	0.20	0.12	1.27
Combined data (3 chronologies)			mean	0.41	0.26	0.31	0.12	1.23
			standard deviation	0.15	0.06	0.10	0.12	0.21
			± 50% limits	0.10	0.04	0.07	-	-
			± 95% limits	0.30	0.12	0.21	-	-

Code	No.trees[1]	Period (A.D.)	%Y[2]	ANOVA %YxT/G[3]	% other	S/N[4]	Correlation Analysis[5] r all series	r within trees	r among trees
GHC607	8	1890-1978	27.24	29.31	43.45	2.96	0.31	0.59	0.29
LKP609	5	1910-1978	31.20	29.92	38.88	2.25	0.37	0.66	0.33
RTA606	7	1881-1970	22.28	28.46	49.26	1.97	0.26	0.44	0.25
Combined data (3 chronologies)		mean	26.91	29.23	43.86	2.39	0.31	0.56	0.29
		standard deviation	4.47	0.73	5.20	0.51	0.06	0.11	0.04
		± 50% limits	2.99	0.49	-	0.34	-	-	-
		± 95% limits	8.94	1.46	-	1.02	-	-	-

Notes: See Tables 6.1 and 6.4

moderate and mean sensitivity and standard deviation values moderate. Low autocorrelation values probably reflect a short leaf retention period (see Section 6.4.2) and moderate mean sensitivities and standard deviation values suggest a moderate sensitivity to climate.

For the sample period, the analysis of variance results are very similar between the three chronologies with low common variance (%Y) (approximately 27%). Variance due to tree differences is approximately 29% and variance between the different radii, approximately 44%. Signal-to-noise ratios are low (average 2.39) and with a mean common variance of 27%, at least 41 trees would need to be sampled to increase this ratio to 15. Correlation analysis shows the greatest similarity between radii within one tree and the least between different trees.

This distinct group of three chronologies has little in common with the other chronologies; few growth sequences could be reliably crossdated, for example, with those from adjacent timberline *Nothofagus solandri* trees. Because of the variable nature of these sites it is not surprising that considerable non-climatic "noise" is present in the chronologies. More rigorous tree selection could help improve the climatic signal. It would seem likely that as these sites are limiting to tree growth because of a local site factor (i.e. soil moisture retention) rather than a regional factor (e.g. aridity) it is likely that actual limiting sites are small in size and may often be difficult to distinguish from adjacent, more favourable sites. The three chronologies discussed here show the potential of this site type but more work is needed to accurately define it.

6.4.2 Timberline chronology statistics

Nothofagus solandri chronologies from near the alpine timberline in Canterbury and Fiordland formed the largest group of chronologies developed here (16). As was shown earlier (Section 5.4), chronologies developed close to but not right at the alpine timberline are likely to be the most sensitive to climate and for this reason, this species was sampled widely at these sites. The large size of this group of chronologies enabled a more detailed analysis of the dendroclimatic characteristics of this species to be undertaken than was possible for the other smaller chronology groups. Chronologies developed from this species can be considered in two ways. Firstly, as a distinct group of chronologies developed with the same species at similar sites and thus having similar characteristics, and secondly, as a spatial grid of similar

chronologies whose ring width patterns vary in response to different site conditions and regional environmental factors. The correlation and cluster analyses help interpret this second approach and are discussed later. Summarised chronology and sample statistics are presented in Tables 6.6 and 6.7.

These chronologies are characterised by high mean sensitivity and standard deviation values and moderate autocorrelation values which are consistent between the 16 chronologies. Absent rings are common in all chronologies, being over 2% in some. Absent rings are often common to some trees in all chronologies in some years (e.g. 1835). The causes of these widespread absent rings are discussed in relation to flowering and other factors in Section 6.7. Growth rates are slow as would be expected from trees near timberline (and see Section 5.4). These chronologies are the most sensitive developed in the present study with often very pronounced year to year fluctuations in ring width.

The pronounced sensitivity to climate is also apparent in the analysis of variance results with an average common variance of 42% (and in two chronologies greater than 50%). These are the highest values obtained for any Australasian tree-ring chronology. Variance due to between tree differences is low and as in *Nothofagus menziesii*, suggests good site homogeneity. The signal-to-noise ratios obtained are also the highest in the present study and for a mean %Y of 42, only 21 trees need to be sampled to maximise the climatic signal. The correlation coefficients are all high and like the other statistics for this species, differ little between chronologies.

Nothofagus solandri chronologies developed from near the alpine timberline are the most sensitive developed in this study and offer much potential for palaeoclimatic reconstruction. However, the relatively short life of the trees, usually 300 years*, prevents the development of long chronologies. The rarity of preserved wood (in alluvial or colluvial deposits or peat) will also pose problems for extending the chronologies back in time.

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* One tree in Fiordland was approximately 380 years old and is, to the best of my knowledge, the oldest tree of this species yet recorded.

TABLE 6.6 *Nothofagus solandri* (timberline sites) chronology statistics.

Code	No.trees	No.radii	Period (A.D.)	AC[1]	MS[2]	SD[3]	%Abs[4]	MRW[5]
AST630	13	26	1720-1979	0.43	0.38	0.42	1.98	0.56
CGB625	12	24	1740-1979	0.45	0.37	0.41	1.43	1.22
CMP614	16	35	1759-1979	0.47	0.31	0.34	0.50	0.79
DBT629	13	26	1780-1979	0.46	0.35	0.37	1.23	1.03
ENT615	12	23	1744-1979	0.54	0.38	0.40	1.96	1.01
HDC632	12	21	1730-1979	0.49	0.34	0.36	1.37	0.58
LCV631	11	20	1730-1979	0.42	0.35	0.36	0.70	0.79
LGH618	11	20	1740-1979	0.50	0.40	0.42	2.30	0.66
LGS624	15	28	1760-1979	0.46	0.33	0.35	1.43	0.75
MKW626	12	24	1730-1979	0.56	0.34	0.38	2.24	0.95
MTB613	14	36	1758-1979	0.57	0.39	0.41	1.15	0.95
RBW628	14	28	1760-1979	0.44	0.31	0.34	0.76	1.03
SSS627	13	26	1760-1979	0.55	0.30	0.36	0.96	1.14
TKV633	11	19	1630-1979	0.43	0.30	0.33	1.37	0.85
TST634	11	19	1840-1979	0.56	0.36	0.39	1.24	1.35
WDC616	11	22	1747-1979	0.59	0.30	0.35	1.01	1.13
Combined data (16 chronologies)			mean	0.50	0.34	0.37	1.35	0.92
			standard deviation	0.06	0.03	0.03	0.54	0.23
			± 50% limits	0.04	0.02	0.02	-	-
			± 95% limits	0.12	0.06	0.06	-	-

Notes: See Table 6.1

TABLE 6.7 *Nothofagus solandri* (timberline sites) chronology statistics.

Code	No.trees[1]	Period (A.D.)	%Y[2]	ANOVA %YxT/G[3]	% other	S/N[4]	Correlation Analysis[5] r all series	r within trees	r among trees
AST630	10	1860-1979	33.04	7.74	59.22	4.93	0.35	0.42	0.34
CGB625	9	1869-1979	44.49	14.37	41.14	7.36	0.47	0.58	0.46
CMP614	14	1869-1979	39.73	11.87	48.40	9.33	0.42	0.54	0.42
DBT629	11	1880-1979	43.46	17.29	39.25	8.30	0.47	0.65	0.46
ENT615	10	1850-1965	50.45	19.89	29.27	10.00	0.57	0.73	0.56
HDC632	8	1850-1979	38.50	19.98	41.52	4.90	0.42	0.58	0.41
LCV631	8	1840-1979	44.78	14.18	41.04	6.55	0.46	0.60	0.46
LGH618	9	1890-1979	41.30	22.21	36.49	6.25	0.51	0.66	0.50
LGS624	9	1850-1979	35.65	13.91	50.44	5.06	0.40	0.56	0.39
MKW626	12	1880-1979	36.05	10.08	53.87	6.75	0.40	0.52	0.39
MTB613	12	1890-1976	46.60	21.34	32.06	10.64	0.49	0.66	0.49
RBW628	14	1860-1979	38.66	13.01	48.33	8.95	0.41	0.53	0.40
SSS627	10	1840-1979	45.98	15.78	38.24	8.52	0.49	0.64	0.48
TKV633	6	1840-1979	37.93	22.17	39.90	3.68	0.41	0.62	0.39
TST634	7	1850-1979	52.47	11.41	36.12	7.58	0.55	0.67	0.55
WDC616	8	1870-1979	39.13	11.41	49.46	5.12	0.42	0.55	0.41
Combined data		mean	41.76	16.08	42.17	7.09	0.45	0.59	0.44
(16 chronologies)		standard deviation	5.42	5.31	8.33	2.09	0.06	0.08	0.06
		± 50% limits	3.63	3.56	-	1.40	-	-	-
		± 95% limits	10.84	10.62	-	4.18	-	-	-

Notes: See Table 6.4

Distinct groupings of timberline *Nothofagus solandri* chronologies are apparent in the cluster analyses (Figs. 6.2 and 6.3). The two Fiordland chronologies cluster with the *N.menziesii* and *Libocedrus bidwillii* chronologies in the first analysis while in the second, TKV remains with these but TST is placed in a single cluster separate from all others. This same pattern is apparent in the correlation coefficients, with the Canterbury chronologies being highly and significantly correlated with each other (all $P < 0.001$ and a mean r of 0.62 ± 0.10). The Canterbury chronologies are not, however, all significantly correlated with the TKV and TST (Fiordland) chronologies (7 out of 28 correlation coefficients significant at the $P < 0.001$ level and mean r of 0.18 ± 0.11) In fact none correlate significantly with the TST chronology, although TST and TKV are strongly correlated ($r=0.63$, $P < 0.001$). The TKV chronology does correlate significantly with four of the five *N.menziesii* chronologies and TST with one. Both these analyses would suggest that although these two Fiordland chronologies have similar statistical properties to the Canterbury chronologies, the year to year ring width patterns differ and this could reflect an environmental difference; the sites are approximately 400 km apart. However, in several years narrow rings do occur synchronously (e.g. 1830's).

Distinct groupings are also apparent among the Canterbury chronologies in the two cluster analyses. In both analyses the HDC, AST, CMP and CGB chronologies cluster together. In the first analysis (Fig. 6.2) the ENT and LGH2 chronologies also cluster together but no other clear groupings are present. In the second analysis (Fig. 6.3), two further groupings occur at this first level, namely LGS, WDC, DBT, LCV and ENT, LGH2. The SSS and RBW chronologies also cluster together, and are the most dissimilar from all others. The SSS chronology is also the last timberline chronology to cluster with the others in the first analysis. In both cluster analyses, the altitudinal transect chronologies group together but cluster in the same general cluster as the timberline chronologies. The lower altitude chronologies on the transect tend to join into the main cluster last; in the second analysis with RBW, SSS and the drought sensitive RTA chronology. The groupings of the timberline chronologies could relate to several factors: distance apart; aspect, altitude and slope; location in relation to rainfall and temperature gradients; stand history and age; soil drainage. These factors are now considered.

Figs 6.4 and 6.5 show the spatial distribution of the chronologies with the clustering pattern superimposed. In both cases some spatially close chronologies cluster together (e.g. LGH2 and ENT) but other equally close chronologies do not cluster (e.g. SSS and MKW). To investigate further the relationship between chronology similarity and distance, the correlation coefficients between each chronology and their distance apart were regressed and are plotted in Fig. 6.6. A significant ($P < 0.001$) negative regression line was fitted to the data but considerable variation would suggest caution in interpreting this. Nevertheless it would seem likely that as the distance between two chronologies increases, their similarity declines. This is evident between the Canterbury and Fiordland chronologies and is also suggested from the data in Fig. 6.6. This type of relationship would be more evident when looking at greater distances. Over a range of 150 km (c.f. 14 km in Fig. 6.6) Fritts (1976, p.274) observed a similar pattern in *Pinus ponderosa, P.edulis* and *Pseudotsuga menziesii* in western North America. This relationship was most evident with the high frequency (year to year) variance and was little evident in the lower frequencies. Some low frequency variance is common between the Canterbury and Fiordland chronologies, but more chronologies are needed before this can be tested properly. It seems plausible that, as site and local climate conditions become greater with increasing distance apart, long term trends reflecting regional climatic patterns (e.g. temperature) will remain similar. Salinger (1979a) has clearly shown that although local differences occur in individual station temperature records throughout New Zealand, the overall patterns are very similar.

Although aspect, altitude and slope differ between the 14 Canterbury timberline sites (see Table 3.2), it is difficult to interpret the cluster patterns in terms of these as no clear relationships are apparent. However, in both analyses the four sites farthest from the central axis of the South Alps cluster together. It is possible that this may be due to rainfall and temperature gradients across the South Island. Actual climatic data are not available for comparison but from personal observations, periods of strong northwest airflow result in rain in the Black and Academia Ranges (including the Cass Valley) but usually no rain in the lower Craigieburn Range (CGB, CMP) or in the lower Harper Valley (HDC, AST) (Fig. 6.5). However, it is more difficult to account for other groupings in this way.

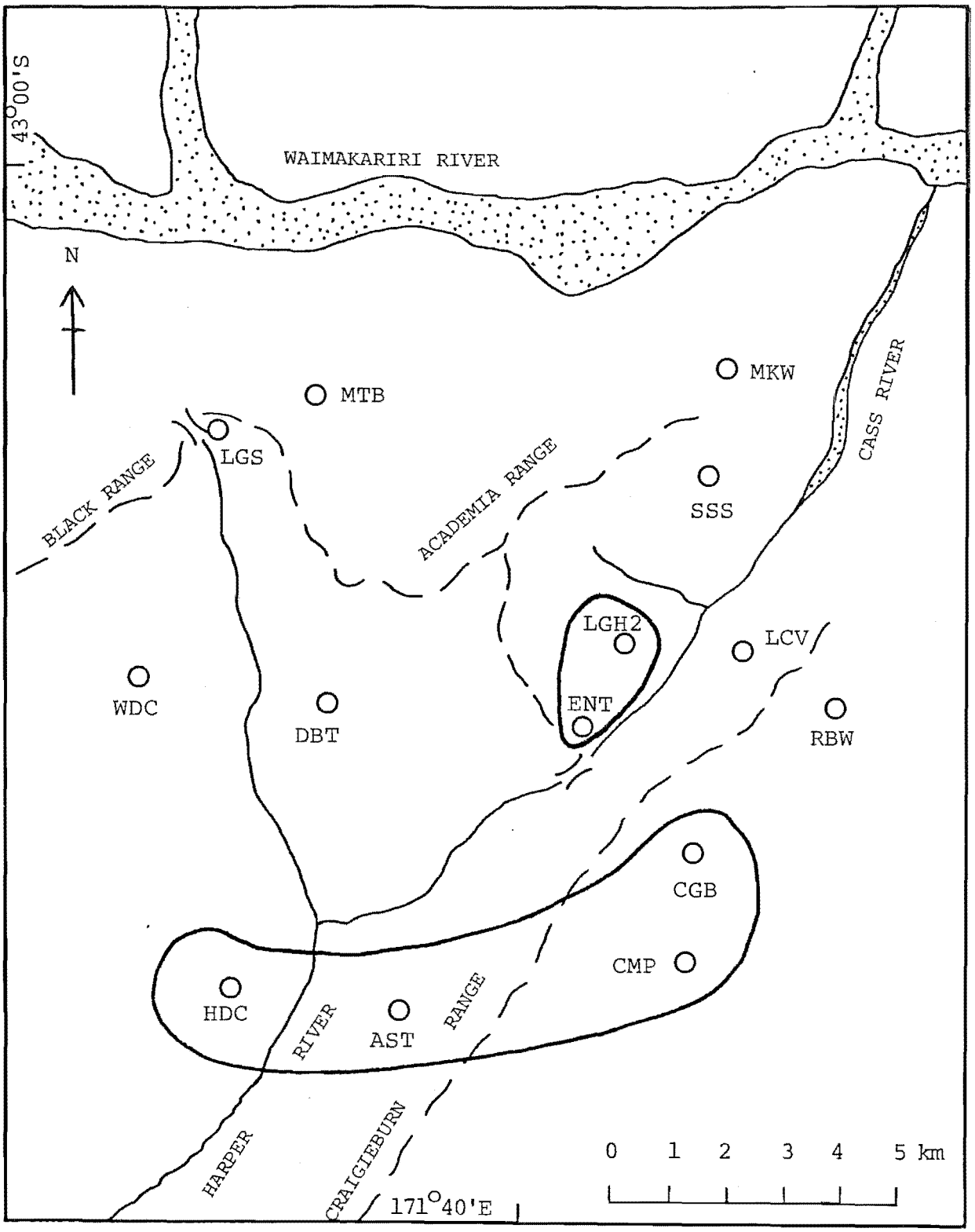


Figure 6.4 Craigieburn Range *Nothofagus solandri* timberline tree-ring chronology sites with the clustering pattern super-imposed (from Fig. 6.2) Only one prominent level of clustering occurred (——).

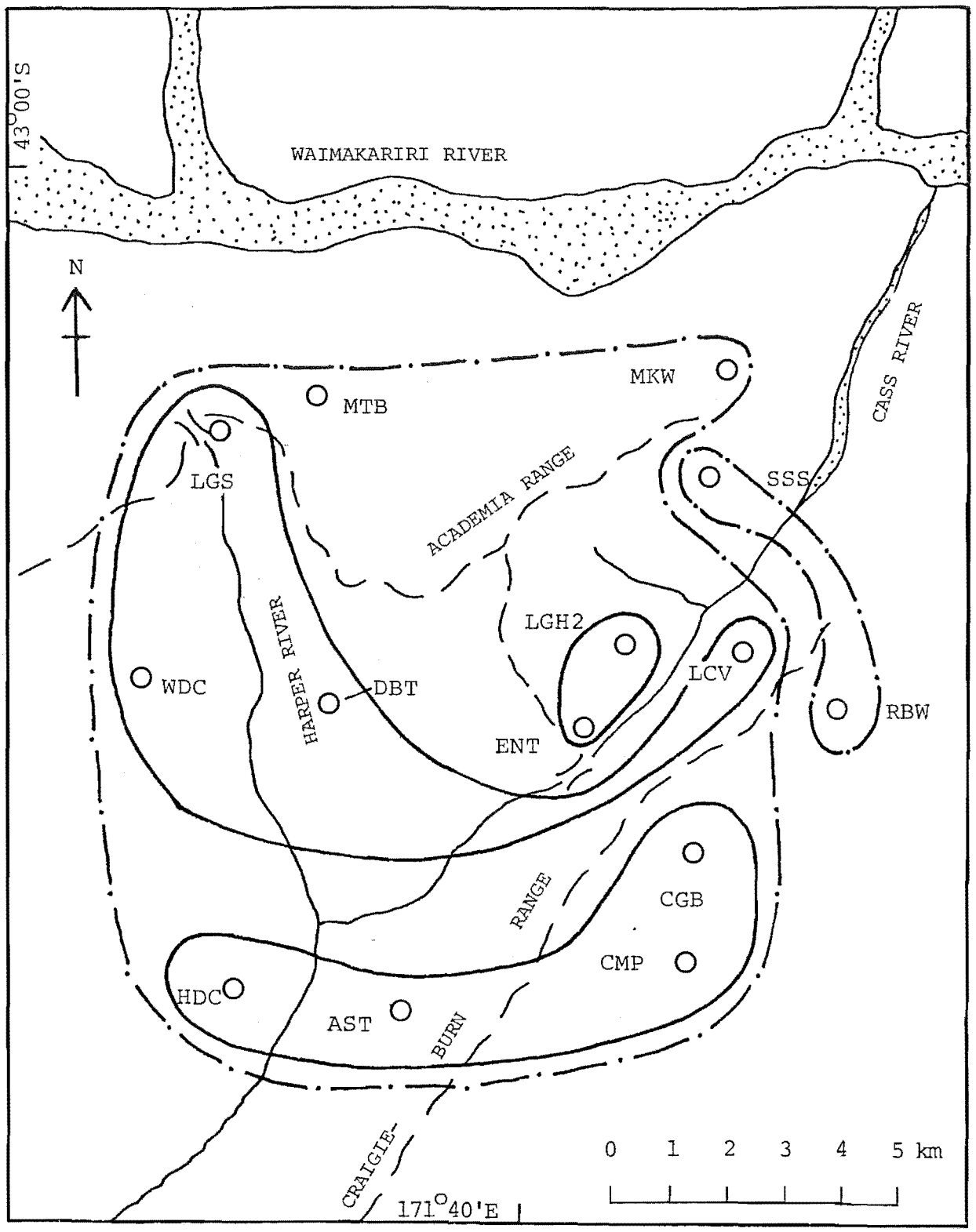


Figure 6.5 Craigieburn Range *Nothofagus solandri* timberline tree-ring chronology sites with the clustering pattern superimposed (from Fig. 6.3). Two levels of clustering are marked. (——) includes the most similar chronologies. (-·——·) includes less similar chronologies.

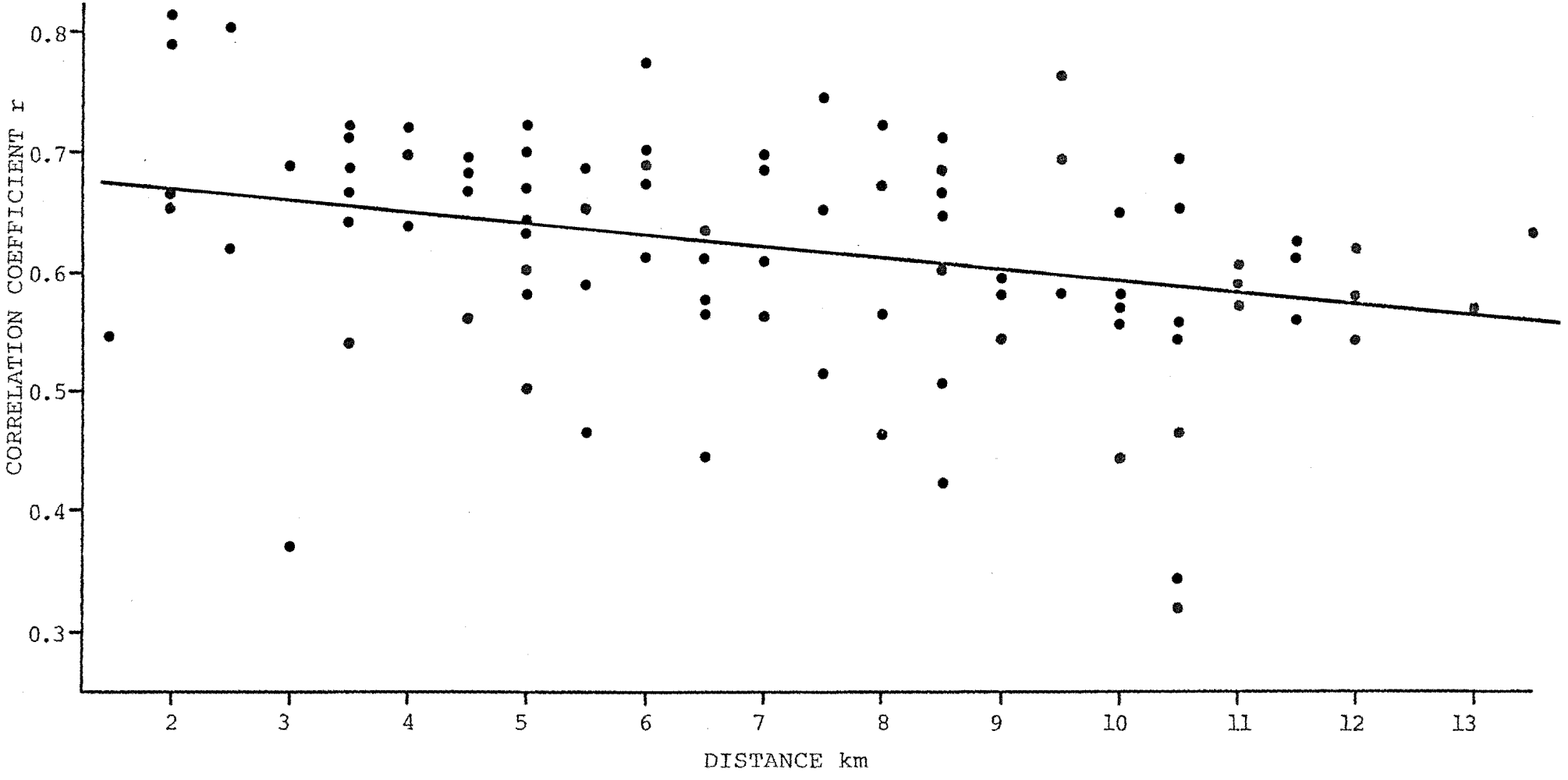


Figure 6.6 Regression of the correlation between each Craigieburn Range timberline *Nothofagus solandri* chronology pair and their distance apart. y=0.691-0.011x, r=-o.340, n=91, P<0.001.

Other explanations for the observed clustering patterns could relate to stand history and stand age factors. Most of the stands are of similar age because of the selection bias towards old stands but the observed differences could relate to some stand history event such as insect epidemic or snow break. Such events could have affected trees in some areas and not others. The occurrence of such events is often difficult to detect (see Section 6.7). Soil features, especially drainage, could also be important but several anomalies (e.g. the wet LGS site clustering with the dry WDC site) suggest this is unlikely to be the overriding control.

It would seem that no one factor alone influences all the sites in the same way, rather a combination of both local and more regional phenomena influence tree growth at each site. It is evident that the distance between two chronologies has a pronounced effect on how similar they are, but a wide range of other factors are also important. As well as variations in tree-ring patterns with altitude (Section 5.4), variation occurs depending on the site location in relation to synoptic weather patterns. Changes in the characteristics of timberline *Nothofagus solandri* chronologies almost certainly will occur as sites further to the east and west are sampled. Despite these differences, *N.solandri* chronologies at the alpine timberline have very similar tree-ring statistics and afford an opportunity to examine the tree-growth-climate relationship over a wide spatial area using chronologies with similar characteristics.

6.5 PSEUDO-CHRONOLOGY

A pseudo-chronology was developed using 12 random number series. Autocorrelation is low (0.05) and mean sensitivity is moderate (0.20) indicating that little persistence remains in the chronology. The standard deviation value is 0.23. In the ANOVA, 3% of the variance is due to similarities between all series while 97% of the variance is attributable to differences between the individual series. An r value of 0.09 was obtained between the individual series. Clearly the pseudo-chronology has almost no common variation present. A signal-to-noise ratio was not calculated as there is virtually no signal in this chronology.

6.6 COMPARISON WITH OTHER CHRONOLOGIES

6.6.1 Chronology statistics

The main chronology statistics (mean sensitivity, auto-correlation and standard deviation) for the four chronology groups developed here, and for a selection of other chronology groups from throughout the world (Table 6.8), are summarised in Figs. 6.7 - 6.9. The arithmetic mean, 50% range and 95% range for each group are given. These three statistics have been used to characterise tree-ring chronologies (e.g. Fritts and Shatz 1975, DeWitt and Ames 1978, Cropper and Fritts 1981) but in all cases only a limited number of chronology groups have been compared. Now that a larger number of chronology groups are available, it would seem desirable to compare these statistics and assess their value for characterising tree-ring chronologies and chronology groups. Based on these statistics, the chronology groups presented here can be divided into two main groupings. The three *Nothofagus* groups are characterised by higher mean sensitivity and standard deviation values and lower autocorrelation values than the *Libocedrus bidwillii* chronologies.

Comparison of these chronology groups with others from both the Southern and Northern Hemispheres helps in interpreting the dendroclimatic strengths and weaknesses of the New Zealand chronologies. Mean sensitivity values are presented in Fig. 6.7. Two distinct groupings of chronology groups are apparent. The *Nothofagus, Phyllocladus* and arid western North American chronology groups are all characterised by relatively high values (0.26 - 0.42). The New Zealand *Phyllocladus* values have the greatest range; probably through the combining of two species *(P.trichomanoides* and *P.glaucus)*. The other grouping of chronology groups has distinctly lower values ranging from 0.13 to 0.20. Except for the New Zealand *Phyllocladus* group, the range of values within each chronology group is small.

The pattern is similar when considering standard deviation values (Fig. 6.8). *Nothofagus* chronology values are again high and similar to the western North American chronology groups. However, the differences are less pronounced with this statistic and more overlap in the ranges occurs between the two groupings. Although the bluff site *N.solandri* group has a large range (in part due to only three chronologies being used), the ranges are still small overall.

TABLE 6.8 Chronology groups compared in Section 6.6. The numbering is used to identify the different groups in Figs. 6.7 to 6.11.

New Zealand[1,2]		
1.	*Nothofagus solandri* (timberline)	n=16
2.	*N.menziesii*	n=5
3.	*N.solandri* (bluff)	n=3
4.	*Libocedrus bidwillii*	n=11
5.	*Phyllocladus trichomanoides)* *P.glaucus*)	n=7
Tasmania[3]		
6.	*Phyllocladus asplenifolius*	n=10
7.	*Arthrotaxis cupressoides)* *A.selaginoides*)	n=4
South America[4]		
8.	*Araucaria araucana*	n=18
9.	*Austrocedrus chilensis*	n=13
Great Britain[5]		
10.	*Quercus petra*	n=14
Eastern North America[6]		
11.	*Quercus alba*	n=16
12.	*Picea glauca*	n=5
13.	*Pinus echinata*	n=9
North American arctic[7]		
14.	*Picea glauca*[8]	n=62
Western North America[9]		
15.	*Pinus edulis*	n=11
16.	*P.ponderosa*	n=21
17.	*Pseudotsuga menziesii*	n=44

Notes:
1. This study
2. LaMarche et al. 1979c
3. LaMarche et al. 1979d
4. LaMarche et al. 1979a, 1979b
5. Pilcher and Baillie 1980a, 1980b
6. DeWitt and Ames 1978
7. Cropper and Fritts 1981
8. This group includes one *Tsuga heterophylla* and one *Larix laricuna* chronology
9. Fritts and Shatz 1975

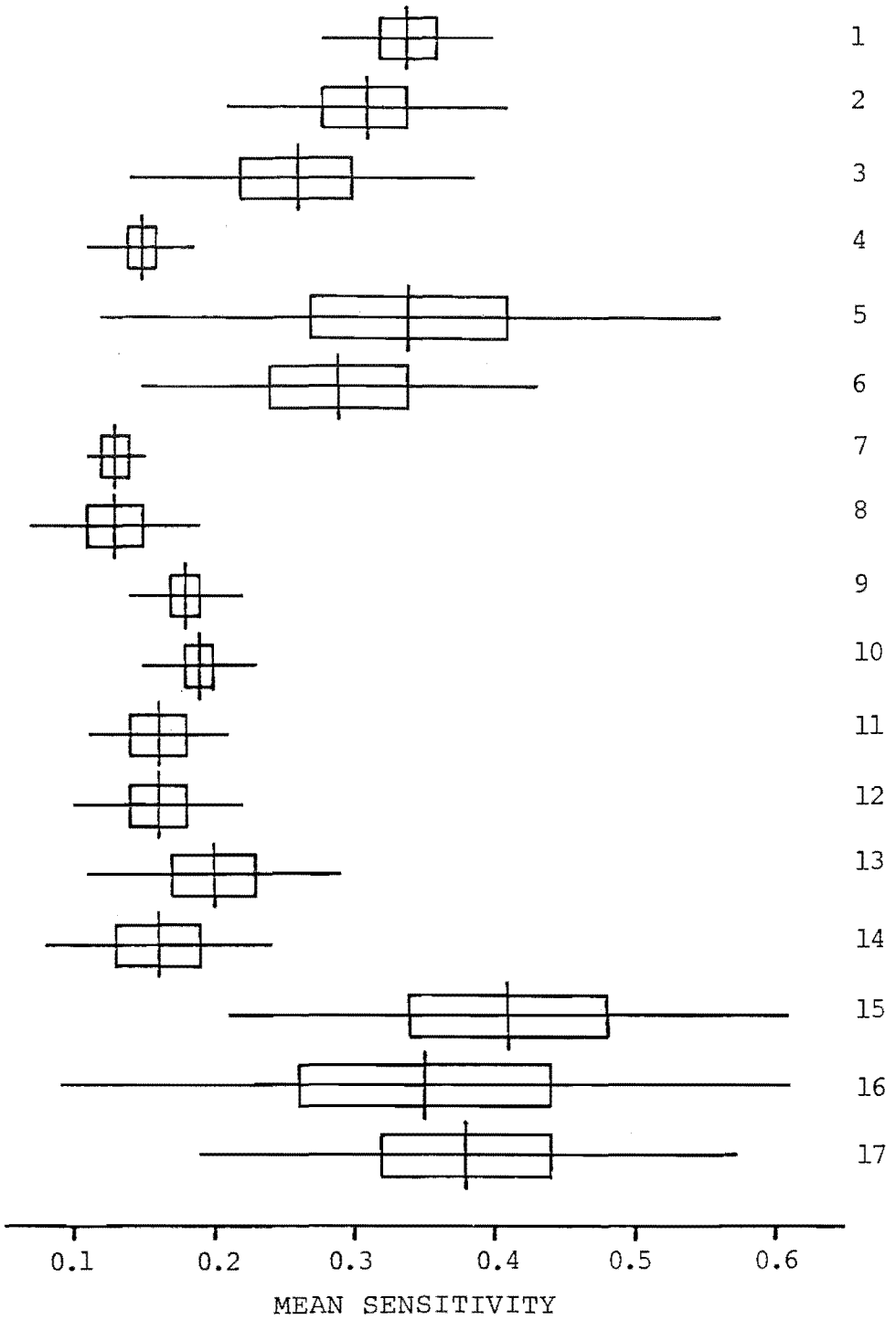


Figure 6.7 Mean value, 50% range and 95% range of mean sensitivity values for different tree-ring chronology groups. See Table 6.8 for key to chronology groups.

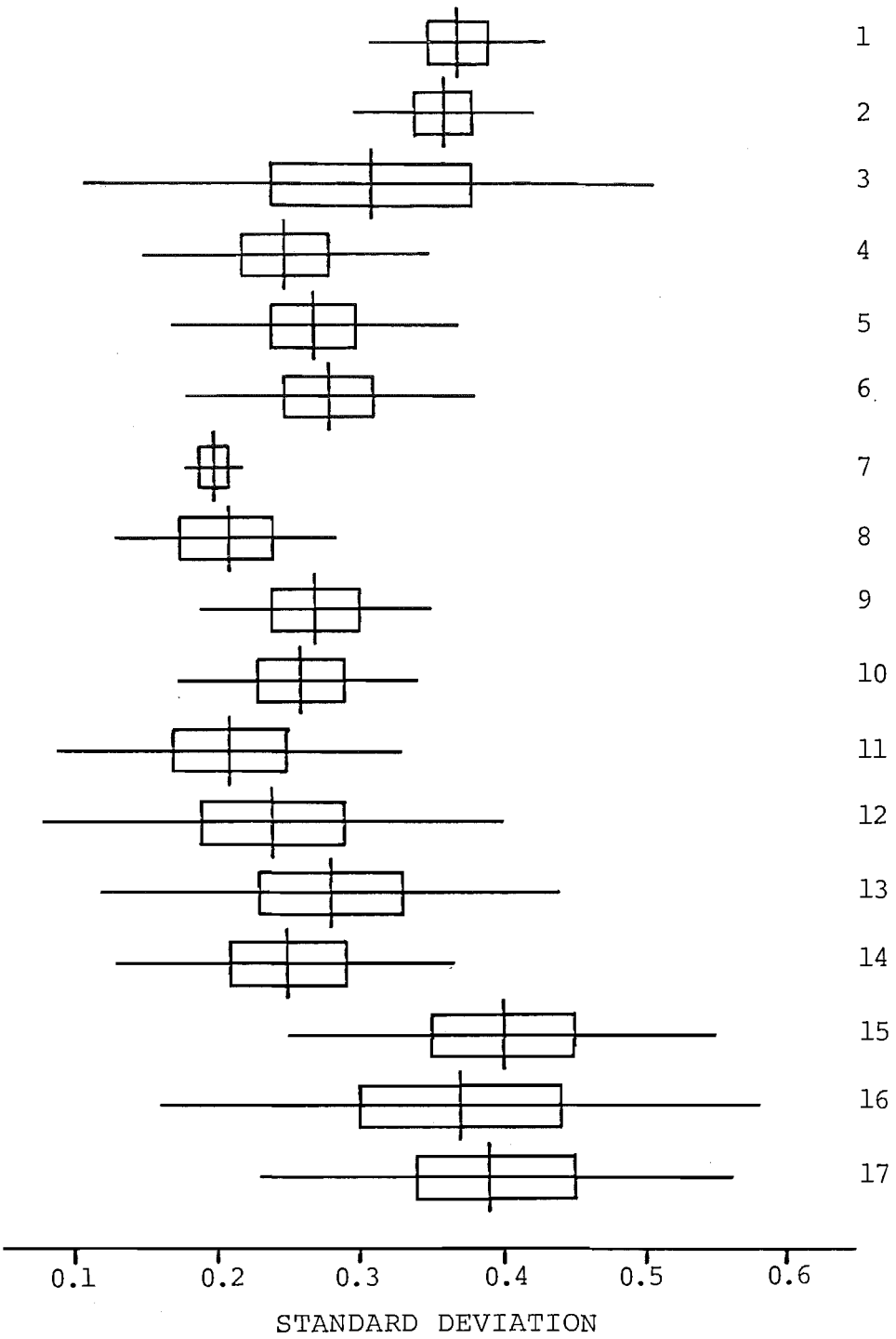


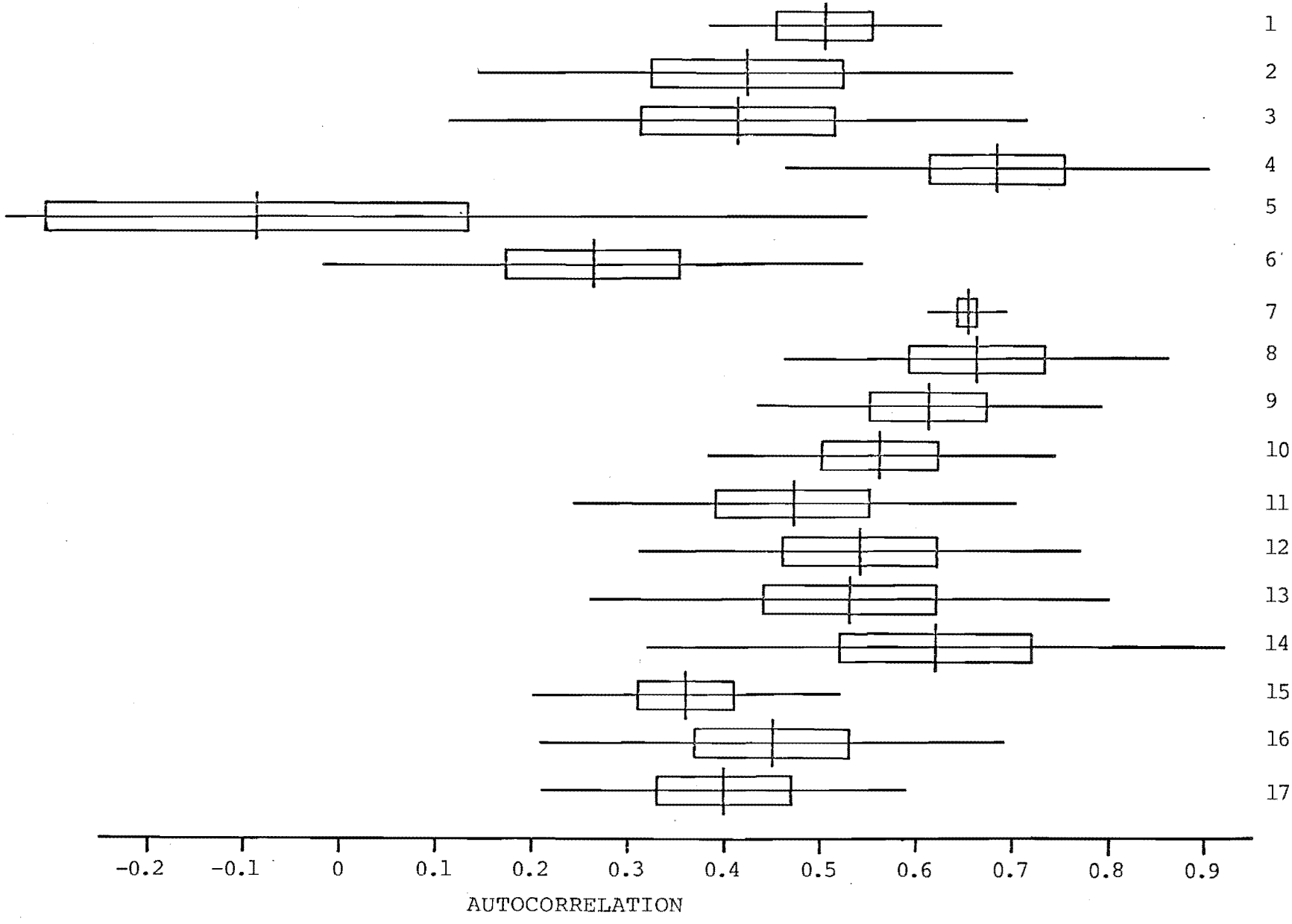
Figure 6.8 Mean value, 50% range and 95% range of standard deviation values for different tree-ring chronology groups. See Table 6.8 for key to chronology groups.

A more complex pattern is apparent in the distribution of autocorrelation values (Fig. 6.9) and the ranges are larger. The two *Phyllocladus* chronology groups have the lowest values. The other groups are more similar with considerable overlapping of ranges. The southern conifers *Libocedrus, Austrocedrus, Araucaria* and *Arthrotaxis* and the arctic *Picea glauca*, have the highest mean values.

The concept of sensitivity is usually associated with climatic responsiveness; "The more the tree has been limited by environmental factors, the more the tree will exhibit variation in width from ring to ring" (Fritts 1976, p.19). This is measured statistically as mean sensitivity. However, high mean sensitivity values are not necessary for the development of tree-ring chronologies; *Libocedrus bidwillii* chronologies with a mean value of 0.15 are evidence of this. Autocorrelation measures persistence in the tree-ring values and is usually inversely related to mean sensitivity. Standard deviation provides a general measure of the total variability in the series. The definition of "good" and "bad" tree-ring chronologies is often implied by these statistics. DeWitt and Ames (1978) define a "good" chronology as "one which exhibits the highest mean sensitivity and standard deviation and the lowest serial correlation". Using this type of definition, the three *Nothofagus* chronology groups presented here and the arid western North American chronologies are the "best", while the southern conifer genera (except *Phyllocladus*) and the arctic *Picea glauca* are the "poorest". However, this type of classification would seem unwise as good climatic reconstructions have been developed using some of these "poor" chronologies (e.g. Holmes et al. 1979, Jacoby and Cook 1981, Cropper 1982, Campbell 1982, LaMarche and Pittock 1982, Jacoby and Ulan 1982). The significance of these statistics therefore warrants further discussion.

The characteristics of tree-ring chronologies change as environmental conditions change. The change in mean sensitivity and autocorrelation with changing altitude shown in Section 5.4 clearly illustrates this. More complex patterns occur in western North America where both aridity and temperature influence tree growth at different altitudes (LaMarche 1974b). However, the differences in chronology statistics between the different species are due to more than just environmental differences.

Figure 6.9 Mean value, 50% range and 95% range of autocorrelation values for different tree-ring chronology groups. See Table 6.8 for key to chronology groups.


1
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16
17
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
AUTOCORRELATION

LaMarche (1982) suggests that there may be some genetical control over the dendroclimatic characteristics of different species and illustrates this using the occurrence of false rings and ring boundary clarity in various conifer genera. The major genetical difference in the data set used in the present discussion (Table 6.8) is between the angiosperms *(Nothofagus* and *Quercus)* and the conifers. However, no clear patterns are apparent. Variation in these statistics could also relate to phenological differences. Ogden and West (1981) observed the occurrence of alternating wide and narrow rings in the New Zealand tree *Beilschmiedia tawa*. This phenomenon is also apparent in other New Zealand trees (Lloyd 1963, Ogden 1982) and is graphically illustrated in *Phyllocladus* (especially *P.glaucus*) with often negative auto-correlation values (Dunwiddie 1979). Ogden (1982) has suggested that this phenomenon may have a physiological basis and it would seem likely that, in view of the considerable impact that flowering and fruiting has on the physiology of plants (see review in Harper 1977), this phenomenon could be related to flowering. The regular alternation of wide and narrow growth rings could indicate biennial flowering in *Phyllocladus*. If this is so, considerable caution is needed in interpreting such chronologies climatically.

Other phenological processes can also have a marked influence on radial growth. The suggestion of LaMarche and Stockton (1974) that the period of leaf retention has an important influence on persistence in *Pinus aristata* tree-ring series is significant. The high autocorrelation values in *Libocedrus, Austrocedrus, Araucaria* and *Arthrotaxis* are possibly due to similar leaf retention phenomena. Using this argument, lower autocorrelation values in *Nothofagus* could then be due to its shorter leaf retention periods (usually one year, J. Wardle 1970d). The values for *Quercus alba* and *Q.petrea* are similar to those of *Nothofagus*. Considerably more physiological information is needed before these patterns can be more clearly understood.

From inspection of chronology statistics discussed here it would seem that mean sensitivity, standard deviation and autocorrelation are influenced by both environmental and biological processes. For example, *Libocedrus bidwillii* trees from near timberline sites have lower mean sensitivity and standard deviation values and higher autocorrelation values than timberline *Nothofagus solandri* chronologies from similar sites in the same area. The occurrence of low mean sensitivity and standard deviation values and high autocorrelation values in *Araucaria araucana* chronologies

from arid sites in South America is contrary to that found in similar arid site trees in western North America. Tree-ring chronologies in both regions have been used successfully to reconstruct past rainfall and riverflow (Fritts 1976, Holmes et al. 1979). In both the examples given it would therefore seem likely that phenological differences have an important influence on the tree-growth climate relationship.

It is therefore unwise to use the statistics discussed above, alone, to define the properties of a tree-ring chronology without a good knowledge of the tree's phenology. Trees with high mean sensitivity and standard deviation values are more likely to have more variable ring width patterns, but they will not necessarily be any more useful for climatic analysis than trees with much less variability. Comparisons such as those done by Fritts and Shatz (1975), DeWitt and Ames (1978) and Cropper and Fritts (1981), although helpful in characterising groups of chronologies, are of little value in deciding what is and what is not a "good" species for dendroclimatic analysis. Rather, for any new species it is necessary to take into account a wide range of factors (e.g. spatial distribution, crossdating, chronology and sample statistics, response function analysis etc.) before deciding whether or not the new species is useful for further and more detailed dendroclimatic study.

6.6.2 Sample statistics

Unlike the chronology statistics, where much of the variation can be accounted for at the species level, the variance sources (Figs 6.10 and 6.11) show less clearly marked patterns and would seem, intuitively, to be more dependent on site conditions. The different sources of variance fall into four main categories; those common to all radii and trees (%Y); those due to differences between trees (%YxT/G); those due to differences between all radii (%YxCxT/G): and those due to differences between radii within each tree (%YxC). This last variance source is usually close to zero (see Section 4.3.5) and is not considered further . Less data are available for comparison of some of the variance sources and for the eastern and western North American species, combined data is available and only for %Y. For *Quercus petrea* only %Y data are available while no data are available for *Picea glauca*.

Common variance is greatest for the western North American chronologies (mean of 60%, no range data available), being considerably more than for any of the other chronology groups (Fig. 6.10). *Araucaria araucana*, from similar semi-arid open stands, has the lowest

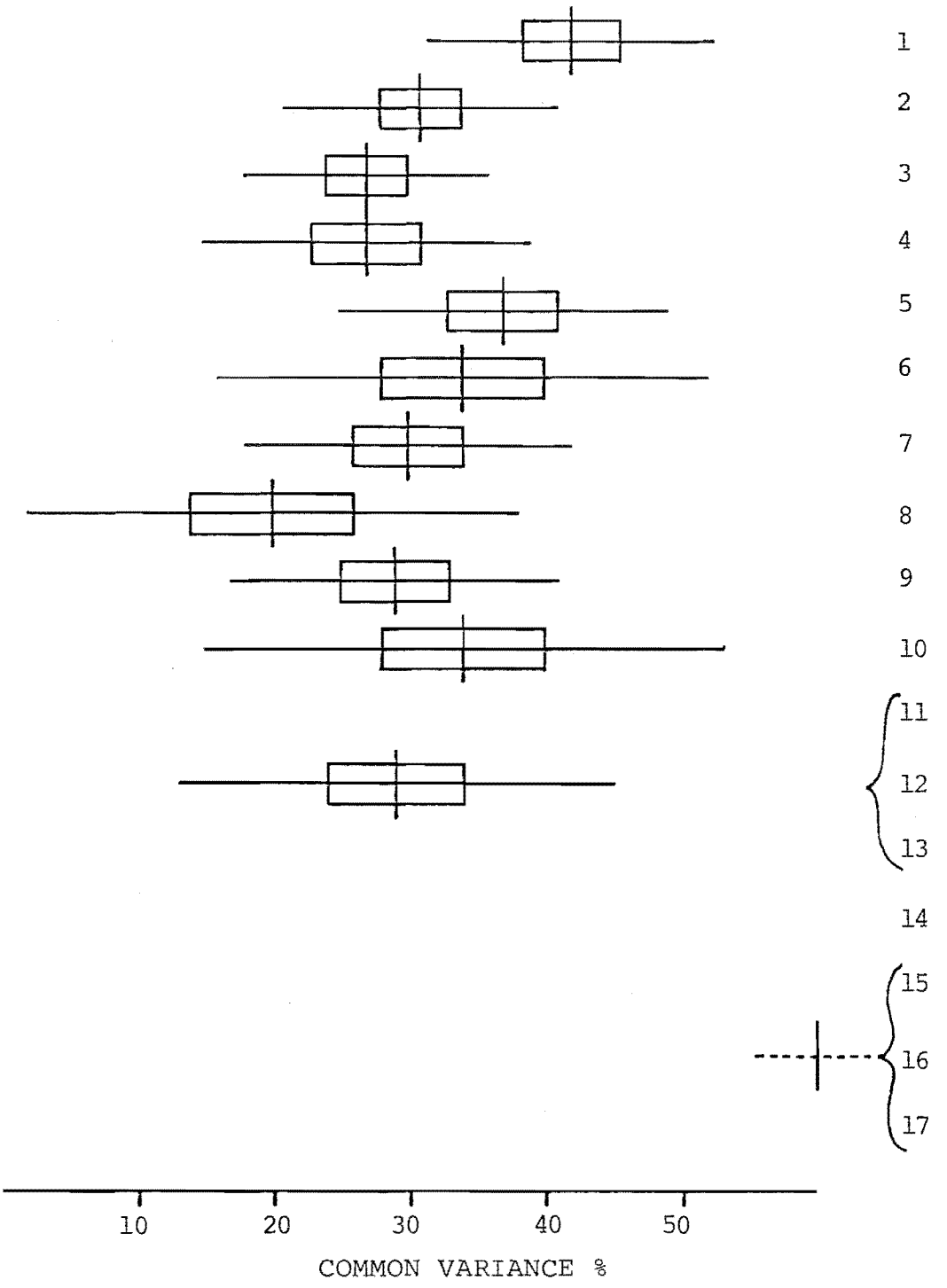

Figure 6.10 Mean value, 50% range and 95% range of common variance values for different tree-ring chronology groups. See Table 6.8 for key to chronology groups.

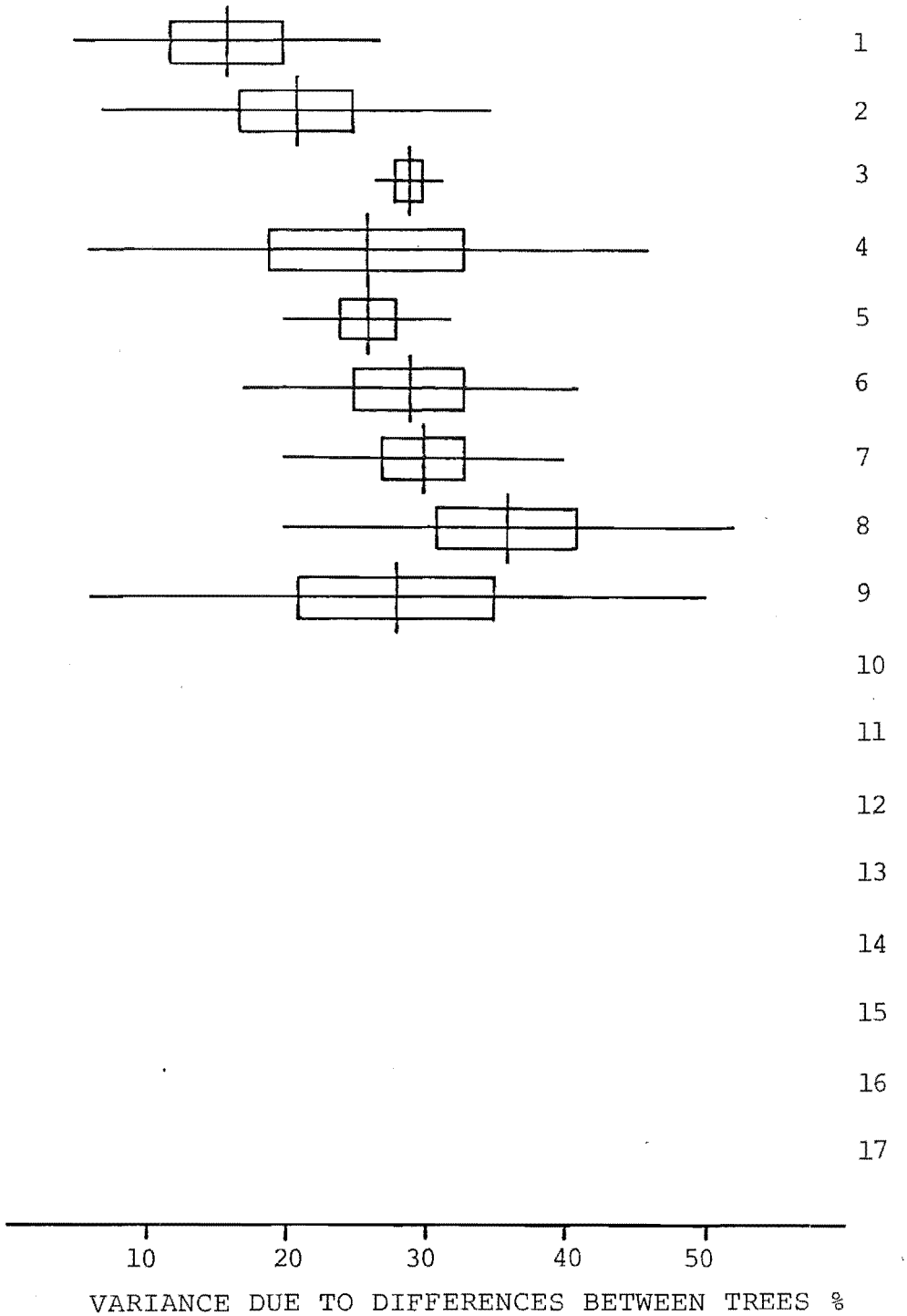

Figure 6.11 Mean value, 50% range and 95% range of variance due to differences between trees values for different tree-ring chronology groups. See Table 6.8 for key to chronology groups.

common variance (20%). Timberline *Nothofagus solandri* chronologies have the next highest common variance (42%) and the other species are very similar with mean values ranging from 27% to 37%. Considerable overlap is present in the 95% ranges, and in most cases the 50% ranges, of the different chronology groups. Variance due to differences between trees is low, being lowest in the timberline *N.solandri* group, and excepting this group, variance due to tree differences are fairly similar. Variance due to differences between all radii (background "noise") are also similar between the different chronology groups.

Of the closed mesic forest stands, those nearest the alpine timberline appear to be more strongly limited by climate, having the greatest common variance. These sites are also the least variable (%YxT/G) (Fig. 6.11). Considering the nine data sets for which complete data are available, the mean variance due to differences between all radii varies from 37 to 48%. This small difference suggests that in mesic forest stands the background "noise" in the tree-ring chronologies is fairly constant. This "noise" is due to the large variety of biological and physical processes which operate within forest stands. Although the nature and intensity of these processes varies between stands, the occurrence of "noise" would seem common to most stands. Also influencing tree growth in these stands are a complex array of climatic factors, some of which may only affect tree growth in certain years and only at certain microsites. As has been suggested in the literature (e.g. LaMarche 1982) the expression of tree-growth climate relations in mesic forests is complex. The balance between common variance and variance due to between tree differences could reflect this complex growth-climate relation.

Despite the similarities discussed above, there is considerable variation present within any one chronology group (e.g. 95% of timberline *Nothofagus solandri* chronologies could be expected to have a common variance ranging from 31.5 to 52.5%). This suggests that the site, rather than the species, is important in determining the common variance. Obviously some species are more likely to vary together in a common fashion because of the nature of the species population dynamics (e.g. open *Pinus ponderosa* forest in semi-arid western North America which has little between tree competition), while others have more between tree interactions (e.g. *Libocedrus bidwillii)*. The interaction between these stand processes and the overriding environmental limitations will then determine the proportions of the different variance sources. Contrary

to the suggestion of Cook (1982), it appears that even in mesic forests, site selection is as critical, if not more critical, than species selection, for optimising the climatic signal in the tree-rings.

The high common variance in the timberline *Nothofagus solandri* chronologies, compared with similar *N.menziesii* chronologies, is possibly due to the inability to develop tree-ring chronologies with the latter species because of very low tree growth rates at sites close to timberline. The lower values of common variance and higher non-climatic variance of the bluff *N.solandri* and *Libocedrus bidwillii* chronologies are probably due to site processes and stand dynamics. The unstable and variable nature of the first chronology group sites, and intermittent regeneration mode of the second, are important.

The use of signal-to-noise ratios (DeWitt and Ames 1978) helps determine sampling strategies to maximise the common variance in tree-ring chronologies. Using the western North American chronologies signal-to-noise ratio of 15 as a base line (10 trees and 60% common variance) it is clearly evident from Fig. 6.12 that considerably more trees are needed to maximise this for other species, including those studied here. With some species (e.g. *Libocedrus bidwillii)*, in excess of 40 trees would need to be sampled. It has been shown by DeWitt and Ames (1978) that the amount of non-climatic "noise" in a tree-ring chronology declines less rapidly with increasing sample size and is relatively independent of the initial starting variance. The importance of the signal-to-noise ratio is that it provides a relatively quick and easy method of assessing the amount of climatic versus non-climatic variance in tree-ring chronologies. An improved signal-to-noise ratio will not necessarily improve the per cent common variance, rather it will reduce the amount of non-climatic "noise". This relates to the need for large sample sizes. When large samples are obtained, the random differences among individuals (i.e. non-climatic "noise") will more-or-less average out (Fritts 1982a). In some species and from certain sites, the number of trees needed to cause this averaging out will be greater than for others.

It can be seen that although the techniques developed in western North America are broadly applicable to other areas, the unique situation of this area has meant that far fewer trees are needed to obtain a strong and clear climatic signal. In other areas, especially in mesic forests, a much greater number of trees are needed to achieve

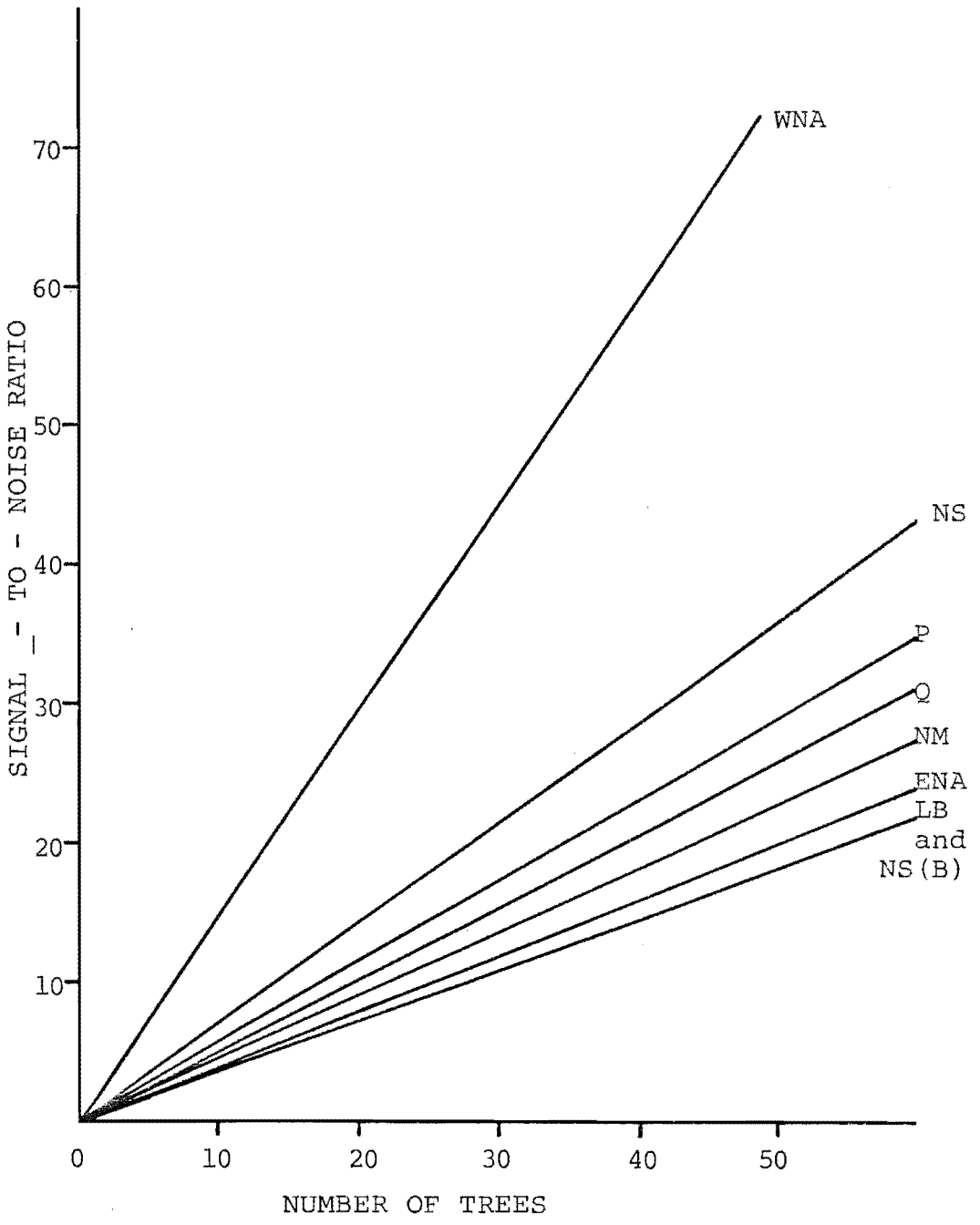

Figure 6.12 Relationship between tree number and signal - to - noise ratio in seven tree-ring chronology groups. WNA, western North America. NS, *Nothofagus solandri*. P, *Phyllocladus trichomenoides* and *P.glaucus*. Q, English *Quercus*. NM, *Nothofagus menziesii*. ENA, eastern North America. NS(B), *Nothofagus solandri* (bluff site). LB,*Libocedrus bidwillii*.

this. Even with a "good" species like timberline *Nothofagus solandri*, at least 20 trees are needed (c.f. 10 in western North America), while with many species considerably more are needed. Except for the timberline *N.solandri* chronologies, the other chronologies developed here are similar in sensitivity to climate and amount of common variance to those elsewhere in the world. *N.solandri* has a considerably stronger climatic signal. It is likely that, with careful site selection, *N.menziesii* could yield a similar amount of climatic information. The response of *Libocedrus bidwillii* is similar to that of other southern conifers (except *Phyllocladus)* and much larger sample sizes would help improve the quality of these chronologies. Too few *N.solandri* bluff sites were sampled to fully assess characteristics of these chronologies. The three chronologies discussed here show the potential of these sites and further investigation would be profitable.

6.7 PROBLEMS IN INTERPRETING COMMON VARIANCE IN TREE-RING CHRONOLOGIES

The techniques of data collection and analysis used in dendrochronology (Chapter 4) aim to maximise variations in ring width common to all trees, while reducing random variance. This is achieved by averaging together many ring width series, with the site chronology retaining variance common to all trees. Because of the criteria used in site selection (Chapter 3) it is likely that much of the common variance is climatically caused and it is therefore possible to use the tree-ring chronologies as proxy records for past climates. However, other factors can also influence tree growth in many trees in a similar way, thus complicating the climatic interpretation of these chronologies. Before the chronologies presented here can be used for climatic reconstruction in Part III it is necessary to assess the influence of these other factors.

6.7.1 "Exceptional" climatic events

In site selection, sites are sampled where it is considered that the rate of tree growth is directly dependent on growing season climate. Tree growth at these sites is influenced by a variety of climatic components (e.g. temperature, rainfall, light intensity) and growth can be restricted when one or several of these components either exceeds or drops below a particular optimum level. The conceptual nature of this relationship has been discussed in Chapter 1 and specific examples are given in Chapter 8. In these situations, climate directly influences growth. This climatic influence can affect several trees in a stand

synchronously. Ring width, as a measure of tree growth, then reflects the aggregate of weather conditions occurring during and sometimes before, the growing season.

Climate can also influence tree growth profoundly when an "exceptional" climatic event* affects trees to an extent that growth over a period of weeks, months or even years, is restricted. The affect of such climatic events usually involves damage to the tree. Depending on the nature of the "exceptional" climatic event, many trees may be affected synchronously and the effects may mimic those caused by shifts in average climatic conditions. The two kinds of climatic influence could, then, be confused in the tree-ring record.

Extensive snowbreak occurs after exceptionally heavy snowfalls and causes considerable crown damage to many trees over a wide area. In *Nothofagus solandri* forests at approximately 600 m near Cass (10 km north of the Craigieburn Range chronology sites) an exceptionally heavy snowfall occurred in August 1973 and resulted in considerable crown damage. In a 2 ha quadrat surveyed shortly after this event, it was found that 78% of the mature trees present (diameter > 0.25 m) had suffered branch breakage due to this and earlier, similar, events (Burrows 1977a). In timberline ecotone *N.solandri* forests in the Craigieburn Range, snow break is important in causing the formation of deformed trees (Appendix 2). The reduction in the area of photosynthetic tissue in affected trees will cause a marked reduction in tree growth increment. Damage of the type described by Burrows (1977a), with breakage of major branches, would require several years recovery time, and would result in reduced growth during this period. It is likely that this growth reduction will be synchronous in many trees in a given stand and thus appear similar to a growth decline caused by, for example, cooler temperatures.

Severe wind damage often occurs in *Nothofagus* forests (J. Wardle 1970d) and can result in the blow down of large areas of forest (Norton and Wilson 1981). Forest stands that are not blown down can suffer

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* "Exceptional" climatic events are defined here as short duration high intensity weather conditions such as exceptionally heavy snowfall or unseasonal frost (see Section 1.4).

considerable crown damage, similar to that caused by snow break. Growth reductions as described above could then occur.

Frost damage occurs frequently enough to trees at and near timberline to provide a useful crossdating tool (LaMarche 1970, Ogden 1978a). Frost damage normally results from unseasonal frosts (either in spring or autumn), when the cells are physiologically active, with distortion of cells in the growth ring. In winter the trees physiological state usually prevents this. Such damage was observed in some timberline *Nothofagus solandri* trees with severely distorted vessels being conspicuous. An exceptionally severe frost, or extensive winter desiccation (Tranquillini 1979, Appendix 2), could result in the death of much of a tree's photosynthetic tissue. This would result in a reduced area of photosynthetic tissue in the subsequent growing season and consequent reduced growth rates until this tissue is replaced. The influence of frost and winter desiccation is often conspicuous in spring, with large areas of dead foliage on trees at the timberline margin (Appendix 2). The influence of these factors on trees in subalpine forest is less clear.

Severe drought events can give a similar effect and in the Craigieburn Range region, because of the known climatic record, such damage would seem likely. Drought is less common in the wetter Westland and Fiordland regions; shallow rooting because of gleyed soils in these areas could, however, cause trees to be susceptible to even short drought periods.

The occurrence of "exceptional" climatic events may be related to longer term general climatic trends. Burrows (1976a) suggested that frequent severe snow storms in the South Island in the nineteenth century were related to periods of cooler climate. Similarly, severe droughts may be part of a pattern of generally lower rainfall. Such climatic trends would themselves be responsible for reduced tree growth which would be enhanced by the "exceptional" events. However, some "exceptional" events such as wind break or severe frost could occur during an otherwise generally favourable period for tree growth.

6.7.2 Insect epidemics

A common feature in New Zealand *Nothofagus* forests is periodic and often epidemic outbreaks of pathogenic insects. Epidemics often

occur after some other factor has reduced tree yigour (e.g. snowbreak or drought) and in one outbreak, one-third of the trees *(N.fusca)* were dead or dying within five years of the epidemic (Conway 1949). *N.menziesii* appears less susceptible to insect attack than *N.solandri* (P. Wardle 1967). Two groups of insects are important; defoliators *(Proteodes* spp.) and pin-hole borers *(Platypus* spp.). Epidemic outbreaks of these insects have directly or indirectly caused widespread tree death, especially in monotypic *N.solandri* forests (Milligan, 1974, J. Wardle 1970d). *Platypus* introduces pathogenic fungi into the tree, with subsequent decay and tree death proceeding rapidly (e.g. within one year, Milligan 1974). A presumably pathogenic fungus has been recorded as spreading from the vicinity of *Platypus* tunnels in living trees (Milligan 1974). *Platypus* and associated fungi are also known to kill *N.cunninghamii* trees in Tasmania (Howard 1973). Epidemic outbreaks of spruce budworm are common in North American conifer forests with marked reduction in radial increment (Williams 1967). The reduction in radial increment was greatest in the upper bole close to the canopy. In Australia, growth rates of *Eucalyptus* can be markedly reduced by defoliating insects (Morrow and LaMarche 1978). Various fungi have similar effects on *Eucalyptus* growth rates (Podger et al. 1980).

Epidemic outbreaks of insects (and associated fungi) can influence *Nothofagus* (especially *N.solandri*) forests in several ways. Two examples serve to illustrate possible effects. Firstly some insect epidemics can cause considerable damage but for various reasons (e.g. weather unfavourable to the insects or tree resistance) do not kill trees, but weaken them. The effect of this would be a marked reduction in growth rate which would last for several years (until the tree recovers). Such damage would be synchronous in many trees in a stand. Secondly, after a severe insect outbreak, the majority of trees may die. The "survivors", after an initial period of reduced growth, will then be able to grow rapidly, possibly for many years, because of reduced competition. As natural regeneration occurs and competition increases, their growth rates will decline again. The detection of growth rate changes in the first case will be difficult as the majority of trees will have been affected in a similar way. However, the "survivors" in the second example will be very large old trees in an otherwise younger, relatively even-aged stand. In the Cass Valley, where it appears that insect damage is causing widespread tree mortality at present, trees near timberline are unaffected. There is possibly some form of

environmental limitation of the activity of the causative insects or fungi at higher altitudes.

Larvae of the ermine moth *Orthenches virgata* were found in the buds of *Libocedrus bidwillii* trees in the Cropp River catchment. Periodic outbreaks of this insect could cause growth rate reductions in *L.bidwillii* trees in a similar fashion.

6.7.3 Flowering and seeding

A further influence on the radial growth in trees is flowering and fruiting. Flowering and fruiting involves a shift in the allocation of resources within a plant (Harper 1977), often occurring at the expense of vegetative growth. Trees that flower and fruit heavily in some years and not in others are said to show periodicity in flowering and fruiting. The occurrence of such periodicity is well documented in some Northern Hemisphere trees (Matthews 1963) and is particularly pronounced in *Fagus sylvatica* (Holmsgaard 1955). In New Zealand, periodic flowering and fruiting occurs in several genera (P. Wardle 1979c) and is very pronounced in *Nothofagus solandri, N.fusca* and *N.truncata* (Poole 1948), but less so in *N.menziesii*. Little is known about flowering and fruiting in *Libocedrus bidwillii*.

In *Fagus sylvatica,* periodic flowering and fruiting years, called mast years, occur after warm dry summers at which time the floral primordia are formed (Matthews 1963). Radial growth is markedly reduced during the mast year resulting in a narrow growth ring, often only half the width of those formed during other years (Holmsgaard 1955, Rohmeder 1967). At poor sites, heavy seed bearing can result in no annual ring being formed at all (Matthews 1963). Holmsgaard (1955) observed that the reduction in ring width associated with mast years was greatest in the upper bole. The occurrence of mast years is the result of the need for the tree to accumulate adequate starch reserves, the hot dry summer initiating flower development.

An average interval of approximately ten years has been suggested between heavy mast years in *Nothofagus solandri* forests (J. Wardle 1970c). It has also been noted that good flowering will not always result in heavy seeding due to the intervention of cold weather which causes flower abortion (Poole 1949). Like *Fagus sylvatica,* flowering in *Nothofagus* appears to be initiated by warm dry conditions in the preceding season.

In Canterbury heavy mast years occurred in 1935-1936, 1948-1949, 1956-1957 and 1966-1967 (J. Wardle 1970c); the first three of these coinciding with years of reduced tree growth in several of the timberline *N.solandri* trees measured in the Craigieburn Range. Temperatures were average or above average in these years and therefore cold temperatures did not limit growth. A reduction in tree growth in 1907-1908 also coincides with a flowering year (Poole 1948).

It would seem likely that, in some years, reduced growth in *Nothofagus solandri* and *N.menziesii* is a result of periodic flowering and fruiting. As mast years occur over wide areas in some years, these will be difficult to detect. However, the frequency of good mast years near timberline is considerably less than at lower altitudes (J. Wardle 1970c). Also there is no evidence that mast years occur in successive years, so that periods of reduced growth lasting more than one year are unlikely to relate to this phenomenon. Further, the influence of most years on radial growth appears to be less in the lower bole of *Fagus sylvatica* trees and a similar response may also occur in *N.solandri*. Comparison between widely spaced sites and different species (e.g. *N.menziesii* and *N.solandri*) should help detect these events. The relationship between mast years and radial growth in *Nothofagus* trees does, however, warrant further research.

6.7.4 Conclusions

Careful examination of the chronologies (Appendix 4) reveals some growth responses to "exceptional" events. The *Nothofagus* mast year of 1907-1908 affected both species of *Nothofagus* in Canterbury and Fiordland. The growth depression associated with this is similar to that occurring during the cool summer of 1904 - 1905. The 1948 - 1949 mast year is apparent in many *N.solandri* chronologies, but lacking in *N.menziesii*. The identification of these events clearly shows that during the recent period (since 1900) exceptional events have influenced tree growth synchronously and over quite wide areas. This will obviously complicate the calibrations of the chronologies with climate discussed in Part III. Variance due to "exceptional" events of both high frequency (e.g. mast years) and low frequency (e.g. insect epidemics) will be present. Low frequency variance due to such events will be very difficult to detect. However, it is likely that the influence of these exceptional events will be less pronounced in the lower bole. There is then a problem of isolating all these kinds of effects in the tree-ring record which must be taken into account when interpreting the chronologies climatically.

6.8 CONCLUSIONS

In Chapters 5 and 6, 33 tree-ring chronologies developed with *Libocedrus bidwillii, Nothofagus menziesii* and *N.solandri* trees have been presented and discussed. All three species have good dendroclimatic potential; they can be crossdated and form chronologies from sites near environmental limits. Trees growing close to the alpine timberline are most sensitive and have a greater common variance than forest interior trees. However, comparison with western North American tree-ring chronologies emphasises the unique situation of this latter group and the need to review sampling strategies in mesic forests. Many of the basic techniques of dendroclimatology were developed in western North America and these techniques are largely used here. It is evident from the results presented here, and in other recent mesic forest studies, that although considerable common variance is present in tree-ring chronologies, the amount of non-climatic "noise" is greater than found in arid-site trees in western North America. Larger sample sizes are needed to reduce this. This applies to the three species being considered here.

Early dendroclimatic research emphasised the importance of site selection in determining the quality of tree-ring chronologies and their usefulness for palaeoclimatic reconstruction. Other work has suggested that for mesic forest situations, species selection is more critical. From the discussion here it would seem more likely that both the species and the site influence the quality of tree-ring chronologies. Obviously as forest limits are approached, the trees become more sensitive to limiting factors, but equally the phenology of the species is very important and must be taken into account. *Nothofagus* spp. seem "better" than *Libocedrus bidwillii,* reflecting both site and species differences. *L.bidwillii* retains its leaves for longer than *Nothofagus* spp. and the tree climate relation is modified because of this. The intermittent regeneration mode of *L.bidwillii* also influences the chronologies with considerable between tree variance present. Differences between low altitude (bluff site) and high altitude (alpine timberline) *N.solandri* sites are pronounced and reflect a local (site) control of tree growth at the first as opposed to a regional control at the second. The low altitude bluff sites are very variable in their limitation of tree growth and the chronologies reflect this with large between tree differences.

An influence little considered in many dendroclimatic studies is that of non-climatic factors causing synchronous and widespread growth rate changes. These can vary from events whose effect may last for several years (e.g. snowbreak and insect epidemics) to those whose influence may be periodic, but is largely over after one year (e.g. flowering and fruiting). The affect of these factors on tree growth in New Zealand trees has been little studied and warrants considerably more research.

Despite the limitations discussed above, the growth of the three species is sufficiently influenced by environmental factors, assumed to be climate, to be used for palaeoclimatic reconstructions.

PART III

CHAPTER SEVEN

DENDROCLIMATOLOGICAL METHODS

7.1 INTRODUCTION

The primary aim of dendroclimatology is to use climatically dependent variations in tree-ring widths to reconstruct past climate. In the following two chapters this is undertaken using the tree-ring chronologies developed earlier. In Part II the occurrence of synchronous variations in the width of annual tree growth rings was discussed and averaged tree-ring chronologies presented. These chronologies were shown to contain variance common to all trees (assumed to be largely climatic signal) and variance particular to individual trees (non-climatic "noise"). The techniques used have been designed to enhance this climatic signal while reducing non-climatic "noise". In this chapter, techniques used to examine the climatic signal further are discussed, and applied to the tree-ring chronologies in Chapters 8 and 9.

Reconstruction of past climates involves two steps, both of which use multiple regression statistical techniques. In *response function* analysis, the climatic components most limiting to tree growth at a particular site (as expressed by the variable ring width indices in the site chronology) are determined by comparing tree growth with recent (twentieth century) climate. From this, tree-ring chronologies whose ring width variations approximate variations in particular climatic components can be identified. In *transfer function* analysis, these groups (or grids) of tree-ring chronologies with similar climatic responses are used to estimate recent (twentieth century) variations in the climatic component of interest. Once this relationship has been established, it is possible to estimate the climatic component for periods prior to instrumental records.

Both response function and transfer function analysis involve *calibration* of a *predictand* time series (either a tree-ring chronology or a particular climatic component) with several *predictor* time series (either several climatic components or a grid of tree-ring chronologies . The term predictors is used in its statistical sense and does not imply a prediction into the future (see discussion in Fritts 1976 p.317).

In calibration the predictors are differentially weighted, in a multiple linear regression equation, to obtain the best estimate of the predictand. Once this relationship has been determined it can be *verified* by applying the calibration weights to an independent set of predictors to obtain predictand estimates. The estimates can be compared with observed predictand values for the independent period and the explained variance calculated. In a transfer function, the calibration weights are then applied to the predictor (a grid of tree-ring chronologies) to obtain estimates of the predictand (a climatic component) for periods before observations of the predictand were made (reconstruction of past climates).

7.2 RESPONSE FUNCTION ANALYSIS

7.2.1 Climate data

Before the response of tree growth to climate can be assessed, appropriate climatic records need to be selected. The records used need to be homogeneous and long enough to be stable during statistical calibration. A wide variety of climatic parameters have been used in dendroclimatology (e.g. number of degree days above $10^{o}C$, Jacoby and Cook 1981), but commonly mean daily temperature and total rainfall are used (Fritts 1976). Other measures such as radiation and evapotranspiration have biological reasons for use but the lack of long homogeneous records in New Zealand makes their use impractical. As the aim of this thesis is to assess the potential of dendroclimatology using New Zealand trees, it was decided to use only mean daily temperature and total rainfall. Even for these relatively simple parameters it was difficult to obtain good records.

Salinger (1979b, 1981) has classified New Zealand into separate response areas for temperature and rainfall; areas that have homogeneous climatic patterns in response to synoptic pressure patterns. Where possible, climate stations falling within the same response area as the tree-ring chronologies were used (Figs. 7.1 and 7.2). For the Craigieburn Range chronologies (including GHC, LKP and RTA), Christchurch temperature and Lake Coleridge rainfall records were used (66 years) and for the CRC, TRK, KEA and Fiordland chronologies, Hokitika temperature and Otira rainfall were used (73 years). The use of Hokitika and Otira data for Fiordland sites is acceptable because of the dominating influence of westerly airflow on the climate of the western South Island (Salinger 1980b, 1980c). No long climate records were available in or

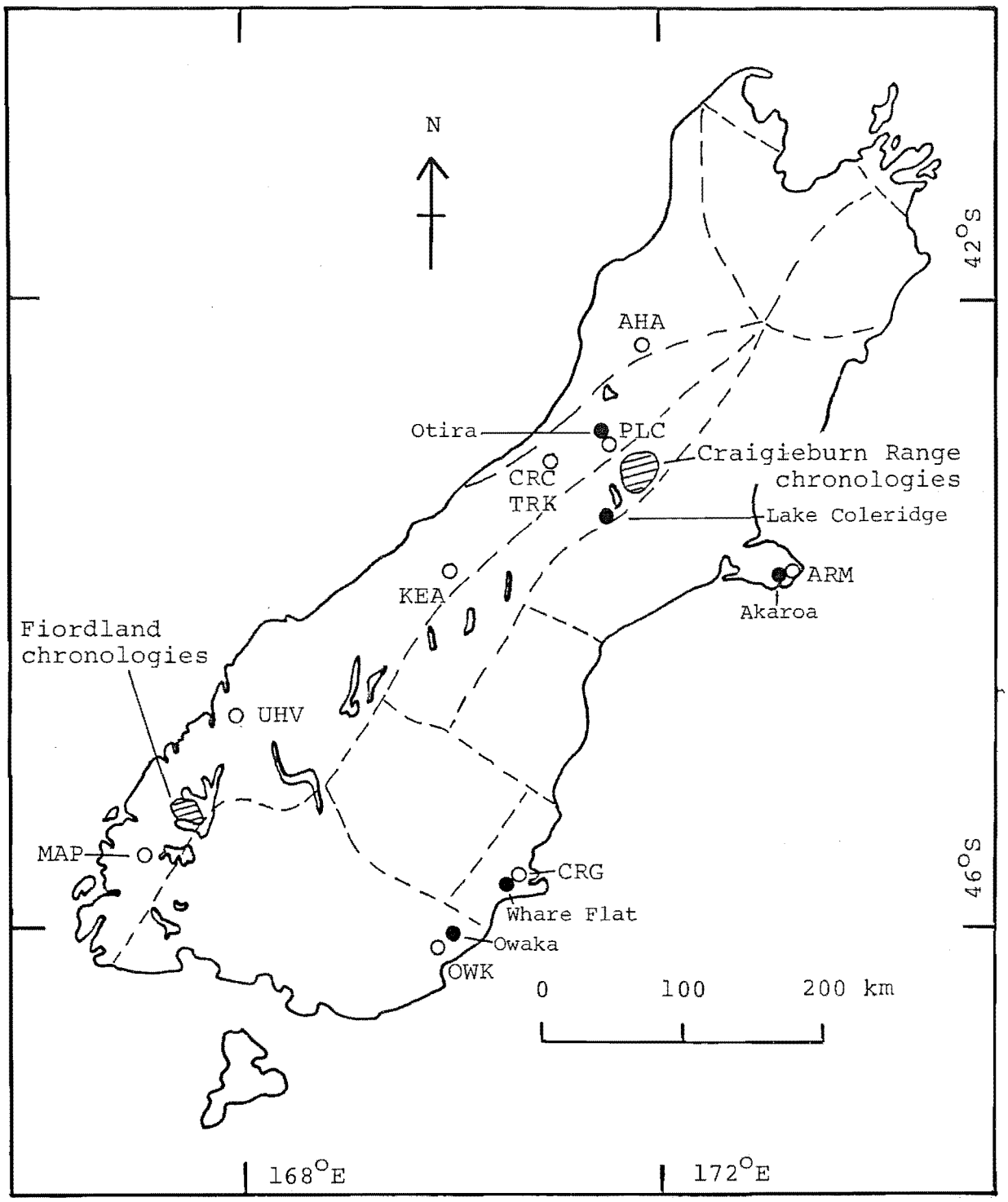


Figure 7.1 Location of rainfall records and response areas (modified after Salinger 1979b) and tree-ring chronologies.

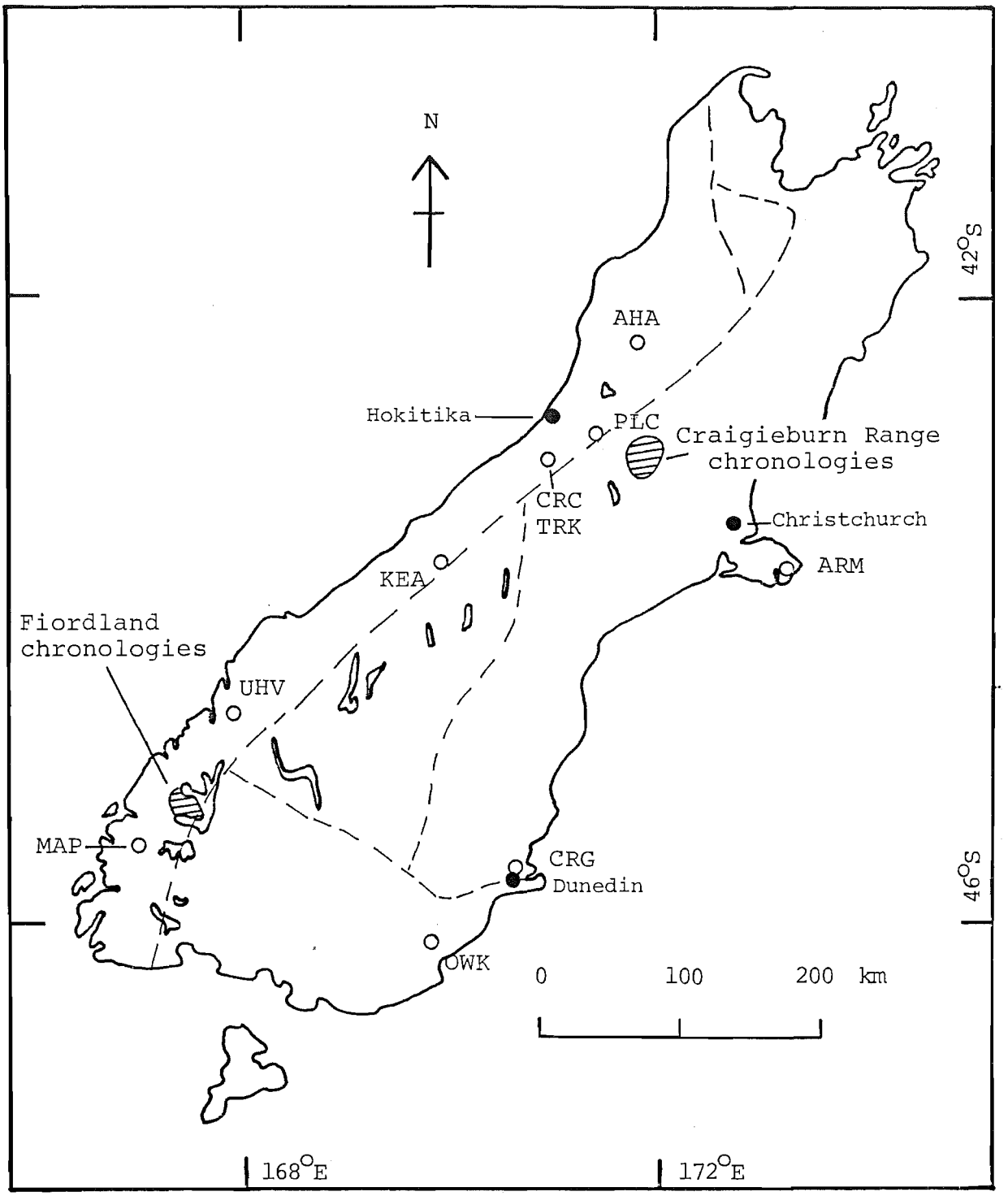


Figure 7.2 Location of temperature records and response areas (modified after Salinger 1979b) and tree-ring chronologies.

near Fiordland; the Milford Sound record only extends back to 1937. Hokitika temperature and Otira rainfall were also used with the AHA (two chronologies), PLC and MAP chronologies developed by LaMarche et al. (1979c). Christchurch temperature and Akaroa rainfall were used with the ARM chronology (74 years), Dunedin temperature and Whare Flat rainfall with the CRG chronology (68 years) and Dunedin temperature and Owaka rainfall with the OWK chronology (62 years). The length of these records is adequate, although longer records would have been desirable. The records used are considered reasonably homogeneous (Salinger 1981).

The climate data can be used in different ways (e.g. annual means or monthly means); previous research (Fritts 1976) has shown that monthly values (means for temperature and totals for rainfall) are adequate for establishing tree growth-climate relationships. The numbers of months of climate data that are compared with tree growth can be varied but to reduce statistical interference between climate in prior (t-1) and current (t) years, only 12 months each of temperature and rainfall data were used. Guiot et al. (1982) found that by using 24 months instead of 12 months, the variance explained did not increase. They also found that interference between prior and current climate gave rise to some spurious regression coefficients. For this reason, 12 months temperature and 12 months rainfall data, starting in June prior to the growing season, were used. The significance of prior climate was assessed by including prior growth in the regression (see Section 7.2.2).

7.2.2 Principal-component multiple-regression analysis

Various techniques have been used to calculate the relationship between tree growth and climate and include sign tests, product means and conditional probability (see Fritts 1976, pp. 329-340). These techniques are only able to consider single limiting factors and are unable to take into account the variable influence of several factors on tree growth. Simple correlations can be calculated between several climatic variables and tree growth (e.g. Norton 1979, 1981b) but because climatic variables are intercorrelated, correlation values can be spuriously inflated. A multiple regression technique using principal components has been developed by Fritts et al. (1971) to overcome these problems and is fully described in Fritts (1976). More recent developments of this technique are discussed by Guiot et al. (1982) and Wigley and Lough (unpublished manuscript).

Essentially the technique first involves removal of inter-correlations in the climate data by reducing these to orthogonal variables through principal component analysis. These orthogonal variables are then regressed against the variable ring width series and finally through appropriate calculations, the regression coefficients are expressed in terms of the original climatic variables. Each site (tree-ring) chronology is analysed separately.

Principal component analysis transforms the intercorrelated climate variables to a new set of uncorrelated (orthogonal) variables. The total variance is the same in both sets, except that in the latter the first variable (principal component) accounts for as much of the total variance as possible, the second variable accounts for as much of the remaining variance as possible while being uncorrelated with the first, and so on (Daultrey 1976). There are as many principal components as there are original variables but the most important principal components account for most of the variance in the data, while the least important principal components reflect only minor variations in the original data set. Usually only a few principal components account for the majority of the variance. Transformation of the climate data to principal components, as well as orthogonalising the data set, allows selection of only the most important principal components for use in the regression analysis. Consequential to this reduction in the number of variables used, is an increase in the number of degress of freedom.

After principal component analysis, the orthogonalised data is used in a multiple linear regression equation of the form,

$$W_i = \sum_{j=1}^{a} b_j X_{ij}$$

where W is ring width in year i (dependent variable), b is the regression coefficient for climate principal component X in year i and q is the number of months data used plus the number of prior growth years (24+3=27) (Wigley and Lough unpublished manuscript). Many of the principal components only explain small amounts of variance (eigenvalues close to 0), often arising from errors or inaccuracies in measurements and their inclusion in the regression can lead to instability in the estimate of the regression coefficients (Guiot et al. 1982 , Briffa et al. 1983). These principal components are eliminated before the

regression analysis using Guiot's PVP method and only those principal components for which the cumulative product of the eigenvalues, multiplied in decreasing order of magnitude, exceeds one, are retained (Guiot et al. 1982, Wigley and Lough unpublished manuscript).

As considerable persistence is often present in tree-ring chronologies, it is necessary to take this into account. The occurrence of significant autocorrelation suggests that climate may influence tree growth over more than one year. This persistence can be taken into account in several ways (see Guiot et al. 1982). The method used here is that recommended by Wigley and Lough (unpublished manuscript) and involves introducing prior growth into the principal component analysis. Prior growth is introduced into the analysis at the same level as the monthly climate data and is reduced to orthogonal variables in the same way as the climate data. Therefore each principal component contains some information on prior growth. They advocate this approach "both on rigorous statistical grounds and on the grounds of computational simplicity and stability" and consider the method of Fritts (1976), whereby prior growth is introduced into the regression at the same level as the principal components, as defeating the purpose of principal component analysis as the data is then not fully orthogonal. Three years' prior growth were used here.

The next step is to enter the principal components into the regression. Since the principal components are orthogonal, each regression coefficient is calculated independently using simple regression techniques and step-wise multiple regression (Fritts 1976) is unnecessary. The statistical significance of each predictor is tested using a *t*-test and only those predictors with *t*-values greater than one are retained. There is no universal method to determine the number of predictors retained and the use of *t*-values is one of several possible methods. What is important is that the method is objective and applied consistently. *t*-value selection has been used successfully in other studies (e.g. Briffa et al. 1983). This step results in a reduced number of predictors in the regression.

Once the regression analysis has been performed, the equation is transformed back to the original variables and confidence limits calculated. These were calculated using the method of Guiot (see discussion in Wigley and Lough unpublished manuscript). An alternative method (Fritts 1976) was not used as it was found here to give

narrower confidence limits and thus was less rigorous. The regression coefficients and their 95% confidence limits are then plotted for interpretation.

The statistical significance of response functions can be calculated in various ways. The correlation coefficient, r, is easy to use and gives an indication of how similar the estimate from the regression is to the observed values. Another test uses the F-distribution where,

$$F = \frac{R^2(n-k-1)}{(1-R^2)K}$$

with (n,n-k-1) degrees of freedom (Briffa et al. 1983). n is the number of data points, K is the number of predictor variables and R is the multiple correlation coefficient. The probability of obtaining the calculated F value by chance can then be calculated. Gray et al. (1981) have presented a test based on the Binomial distribution for assessing the number of regression coefficients significantly different from zero (95% level) that can occur by change. They found that for 24 or 28 predictor variables, at least 4 coefficients must be non-zero at the 95% level to get an overall result that is significant at the 95% level. The significance of response functions is discussed further in Chapter 8.

7.2.3 Limitations of response function analysis

As with any statistical technique used to describe natural phenomena, response function analysis has several weaknesses. The most obvious is the difficulty in describing such a complex and variable system as tree growth in a linear equation. Climate is not the only factor that influences tree growth (see Part II) and the climatic influence itself is complex and variable. It is naive to think that monthly temperature and rainfall alone limit tree growth. Rather the influence of climate is through a variety of factors such as radiation, evapotranspiration, wind and frost as well as temperature and rainfall (see figures 5.8-5.10 in Fritts 1976). However, much of the variation can be expressed in terms of these latter two variables and because of the inadequacies in instrumental climate records one is forced to use them. Generally, long instrumental records are only available for temperature and rainfall. Further problems can arise because of the non-linear response of tree growth to climate. Logarithmic or other transformation techniques may help overcome this problem.

A second major weakness has already been mentioned; that is how to take into account the influence of prior climate. It has been repeatedly shown that prior climate does influence growth because of interactions with prior growth (Fritts 1976). In the response functions used here this has been taken into account by introducing prior growth into the principal component analysis. Other techniques such as deautocorrelation, where persistence is removed from the tree-rings prior to regression (Guiot et al. 1982, Wigley and Lough unpublished manuscript), may be more appropriate, but such techniques have yet to be adequately tested. If persistence is removed from the tree-ring series it should also be removed from the climate record.

A third weakness arises from the failure to separate out short term and long term climate influences on tree growth (Fritts 1976). A multivariate spectral technique that examines the growth-climate relationship at different frequencies, has been developed (Guiot et al. 1982) and shows considerable potential.

Despite these weaknesses, response function analysis is a useful tool for examining the growth-climate relationship and, if interpreted judiciously, can give considerable information. The safest way to use response functions is with good replication and verification. Response functions from several chronologies should be examined and then verified with independent data sets.

7.3 TRANSFER FUNCTION ANALYSIS

7.3.1 Introduction

Reconstruction of climatic records involves the transfer of climatic information from the annual growth rings to estimates of climate. The selection of suitable tree-ring chronologies to use is based on the response function results. Reconstruction involves the calibration of the tree-ring chronologies (in a similar way to a response function) followed by verification of this relationship with independent data before an actual reconstruction can be determined.

Early climate reconstructions were largely undertaken with trees growing in very limiting environments (e.g. arid western North America, Douglass 1928); tree growth being strongly limited by one over-riding factor (e.g. rainfall). The development of multivariate statistical techniques in recent years (Fritts et al. 1971, Fritts 1976, Lofgren

and Hunt 1982) has resulted in considerable progress in dendroclimatic reconstructions, both in traditional areas (western North America) and elsewhere (e.g. eastern North America, Great Britain, Tasmania). Reconstructions usually take one of three forms; local climate records (e.g. Schweingruber et al. 1978, Jacoby and Cook 1981, Conkey 1982, LaMarche and Pittock 1982, see below), regional climatic records (e.g. Pilcher and Hughes 1982, Briffa et al. 1983, see below), and gridded climatic records (e.g. Fritts 1976, Fritts et al. 1979, Kutzbach and Guetter 1980). Reconstruction of other parameters such as freezing over of rivers (Jacoby and Ulan 1982) and riverflow (Holmes et al. 1979, Campbell 1982) are also possible.

7.3.2 Tree-ring chronology grids

Temperature or rainfall and tree growth at any one site are influenced by microclimate, local climate, and regional climate (see Section 1.4). Microclimates differ considerably over short distances; geographically close tree-ring chronologies and climate stations are often influenced by quite different microclimate conditions, although local and regional influences are similar. Local climate anomalies are prominent in New Zealand because of the diverse topography. Local anomalies of opposite trend can occur in adjacent areas as a result of the same synoptic climate pattern. Because of microclimate differences, it has been found that the most successful reconstructions are achieved using regionally averaged climate records (Blasing et al. 1981). A good spread of tree-ring chronologies is necessary to reconstruct local or regional climate, as individual chronologies are responding slightly differently. Combined together several tree-ring chronologies can best approximate local or regional climate. Grid size and density is then an important consideration for maximising the climatic signal being reconstructed (Kutzbach and Guetter 1980).

For reconstructing atmospheric circulation patterns, Kutzbach and Guetter (1980) have suggested that tree-ring chronology sites should be evenly distributed over the area of interest and at as high a density as practical. They also found that best results were obtained when the tree-ring grid covered at least twice the area for which the reconstruction was being determined. Fritts (1982b) has, however, pointed out that often it is better to concentrate sampling in areas where trees are particularly sensitive to climate, rather than to develop even grids.

As the present study was not attempting to reconstruct circulation patterns, the need for an evenly spaced grid of chronologies was less critical. However, it was still necessry to have a good spatial spread of tree-ring chronologies. This was achieved here, at least for the timberline sites, by using *Nothofagus* chronologies from the Craigieburn Range, South Westland and in two areas of Fiordland. A much smaller grid of drought sensitive tree-ring chronologies was also used. The grids used for reconstruction are discussed further in Chapter 9.

7.3.3 Climate data

Reconstruction of both local and regional climate records, and of riverflow, were undertaken. Because of similarities in temperature variations throughout New Zealand (Salinger 1979a), it is possible to derive a regional New Zealand temperature series. Such a temperature series has been developed by Salinger (1980a) and incorporates temperature records from Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln College (near Christchurch) and Dunedin (Fig. 7.3). This series, which extends back to 1853, is considered a homogenous regional temperature record and was used here.

Rainfall anomalies are strongly localised in comparison to the more regional temperature anomalies (Salinger 1980b, 1980c), although some workers (e.g. Vines and Tomlinson 1980) have suggested, based on filter analysis, that considerable similarities still do occur in rainfall patterns throughout New Zealand. However, because of the more compelling evidence for strongly localised rainfall patterns (Salinger 1979b, 1980b), records from individual stations were used here. Rainfall records from five stations with good quality long records were chosen. The stations - Highfield, Amberley, Lake Coleridge, Ashburton and Orari Gorge - are all in Canterbury (Fig. 7.4), within approximately 100 km of the drought sensitive tree-ring sites. All the stations lie within either the Canterbury or Alpine spillover rainfall response areas (Salinger 1979b). The tree-ring sites are in the Alpine spillover area. The selection of suitable rainfall stations is discussed further in Chapter 9.

Riverflow is directly dependent on rainfall runoff and can be reconstructed using drought sensitive tree-ring chronologies (e.g. Holmes et al. 1979, Campbell 1982). However, the short length of the riverflow records makes this difficult for many New Zealand rivers.

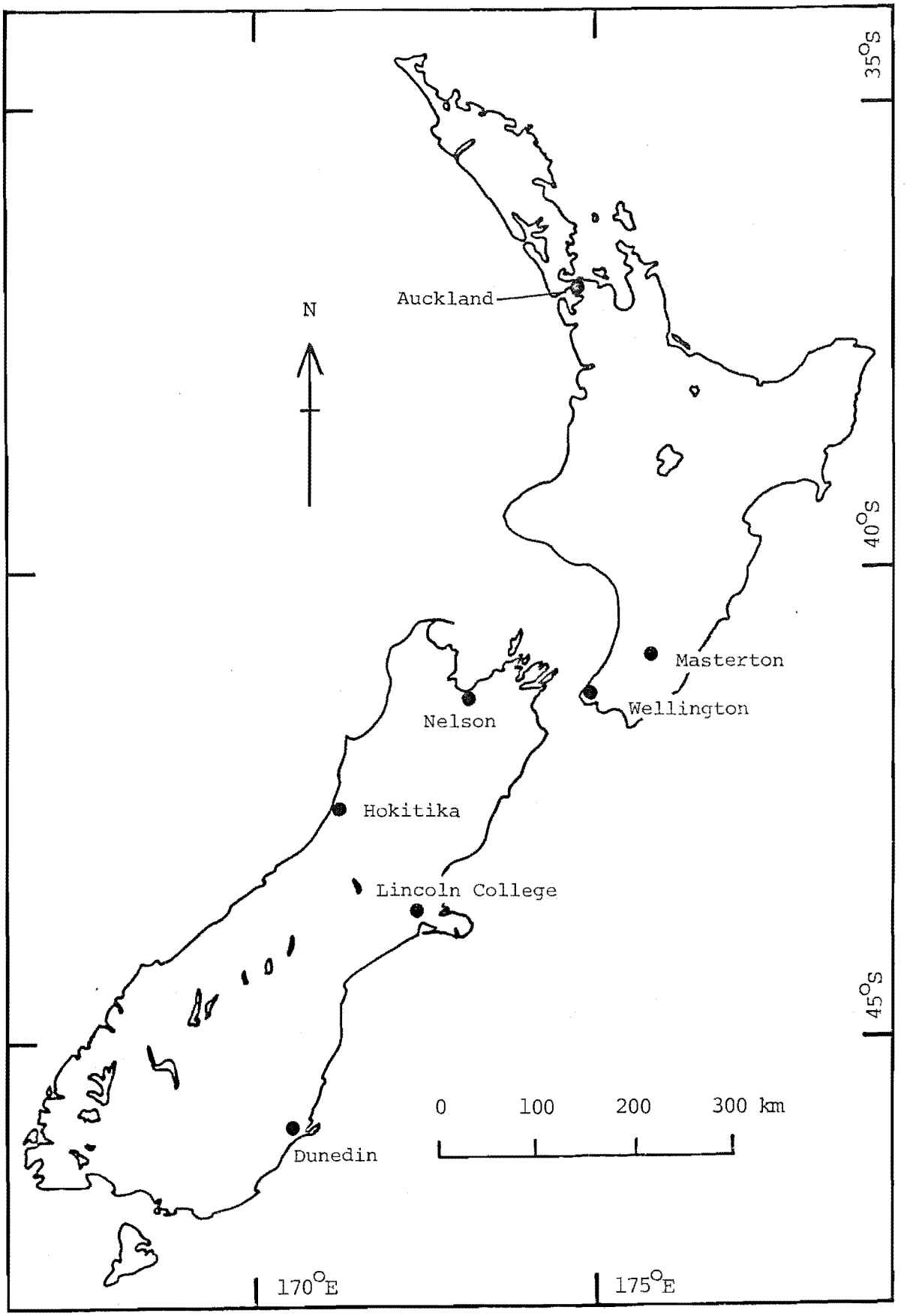


Figure 7.3 Location of temperature stations used to develop the New Zealand temperature series.

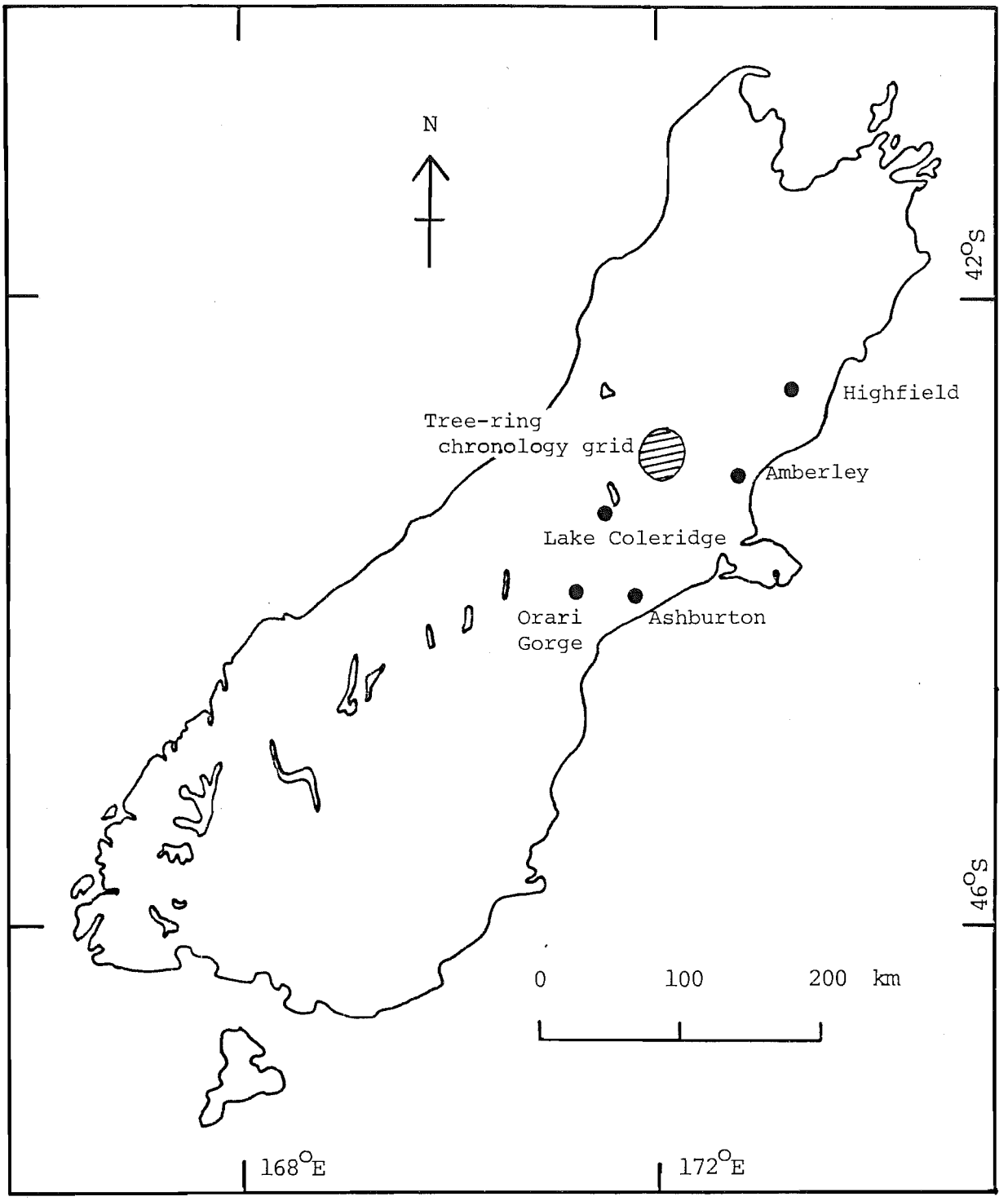


Figure 7.4 Location of Canterbury rainfall stations and the rainfall sensitive tree-ring chronology grid.

To reconstruct riverflow it is necessary that the river's main catchment area is influenced by the same rainfall producing synoptic situations as the tree-ring chronologies. In Canterbury, the main river catchment areas (Rangitata, Rakaia and Waimakariri Rivers) extend along the main divide of the Southern Alps and are located at high altitude (e.g. 28% of the Rakaia catchment is above 1500 m, Bowden 1977). Riverflow in these rivers is strongly correlated with rainfall associated with westerly airflow (Ibbitt 1979). Because of this, riverflow reconstruction has, of necessity, been confined to rivers whose catchments occur mainly in the eastern ranges, where the drought sensitive tree-ring chronology sites are also located. Of the suitable rivers, Hurunui River has the longest record and drains a short section of the main divide with only 8% of its catchment above 1500 m (Bowden 1977). Several lakes are located within the catchment (see Section 9.4). The water resources of the Hurunui catchment are described in detail by Bowden (1977). The 23 year monthly discharge record for this river was used here.

7.3.4 Statistical Analysis

The rationale for transfer function analysis has been discussed by Fritts (1976) and statistical techniques to undertake this by Lofgren and Hunt (1982) and Briffa et al. (1983). As with response function analysis, transfer function analysis first involves calibration of the predictand series (climate) with several predictor series (tree-ring chronologies). Again principal component analysis is used to select the most important variation in the predictor data set. Both canonical correlation (Lofgren and Hunt 1982) and multiple linear regression (Briffa et al. 1983) have been used for determining transfer functions. In canonical correlation the relationship between two sets of variables can be assessed while in multiple linear regression the relationship between a set of predictor variables and one predictand can be assessed.

The principal component multiple linear regression program used by Briffa et al. (1983) was used here and proved perfectly satisfactory for fulfilling the objectives of the present study. The regression techniques are essentially the same as has been described for response function analysis (Section 7.2.2).

Tree growth in any one year (t) is influenced by both climate that year and by growth in the previous year ($t-1$) (Figure 7.5a).

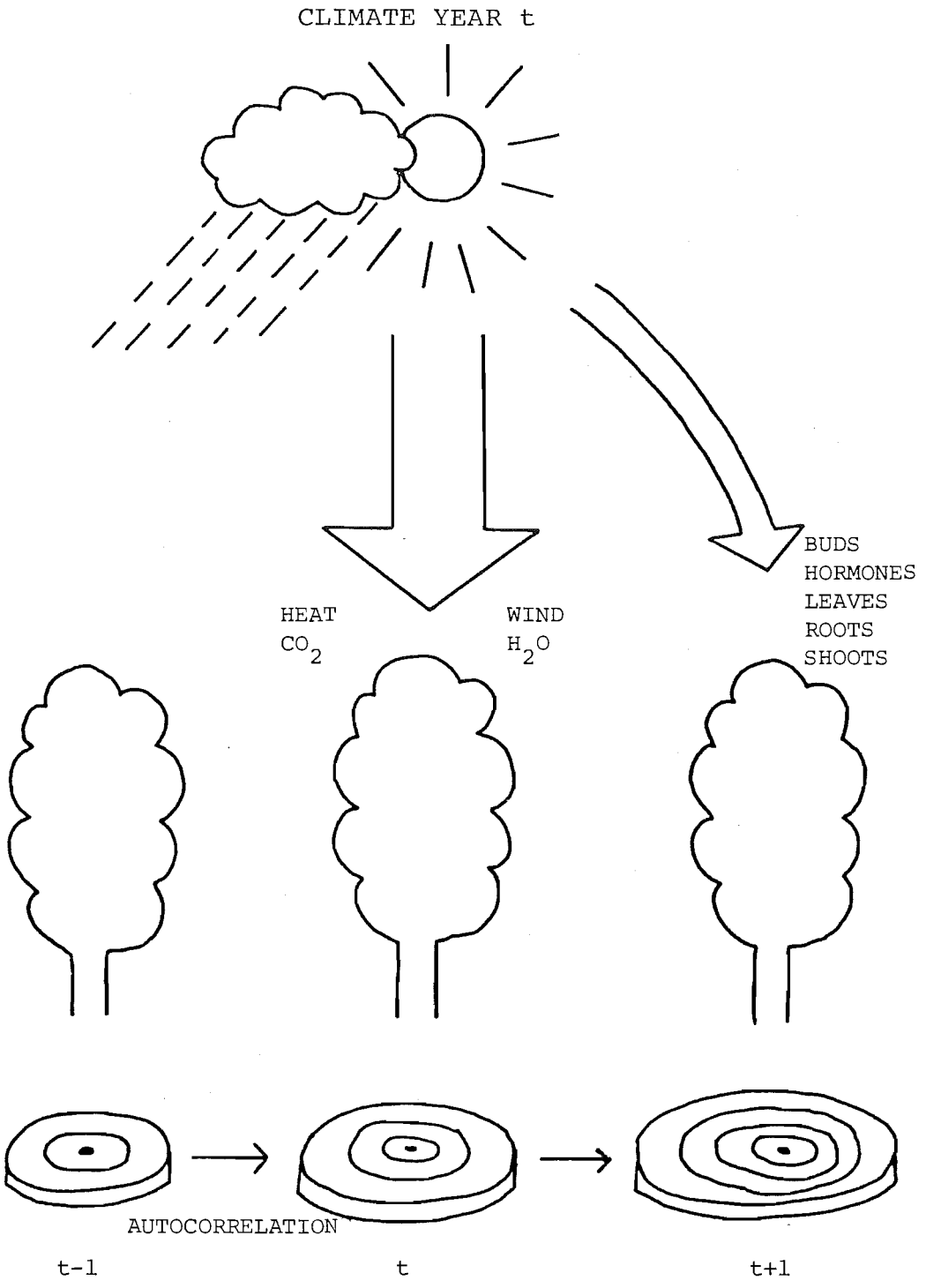


Figure 7.5a The influence of climate on tree growth. Climate in year t can directly influence growth in that year and in year t+1 through its effects on buds, hormones, leaves, roots and fruits. Growth in the previous year (t-1) can also influence current year's growth (modified after Fritts 1976).

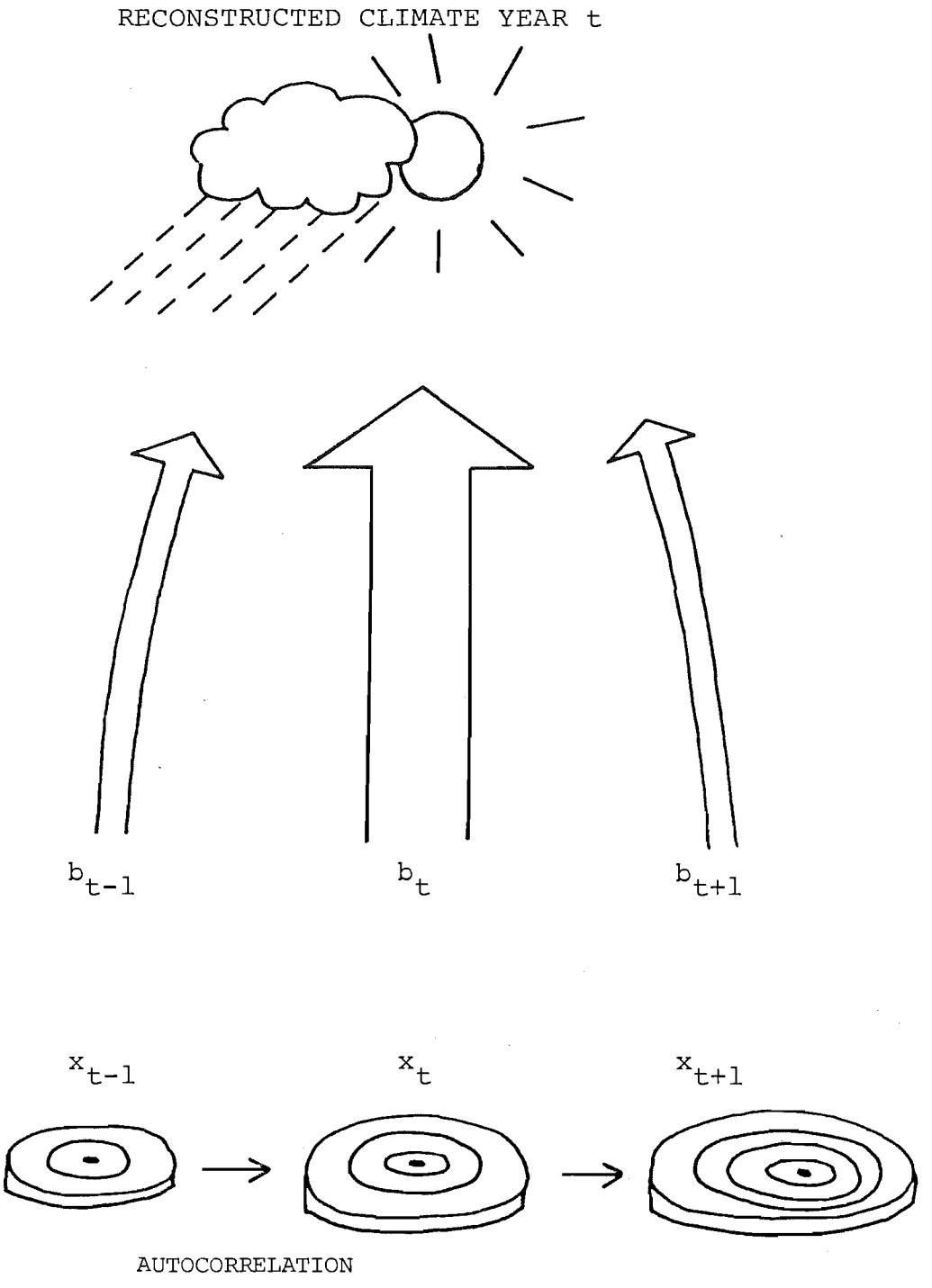


Figure 7.5b The use of tree-rings to reconstruct climate. b_{t-1}, b_t and b_{t+1} are the regression coefficients which can be multiplied by the ring widths x_{t-1}, x_t and x_{t+1} to obtain an estimate of climate in year t. The inclusion of b_{t-1} is to correct the causal linkage for any statistical autocorrelation effects (modified after Fritts 1976).

The effect of climate in any one year also affects growth in the subsequent year (*t+1*) (Fig. 7.5a). To reconstruct climate it is therefore necessary to take into account these prior growth and lag effects. For each chronology, values for years *t-1*, *t* and *t+1* were used as predictors in the regression analysis (Fig. 7.5b).

A major problem with this multivariate statistical approach to reconstruction is the possibility of chance correlations causing the calibration period explained variance to overestimate the usefulness of the regression equation - "artificial predictability" (Lofgren and Hunt 1982). This is most likely to happen when the number of predictor variables is large compared with the number of observations. The number of predictor variables used here was either 15 or 21, and the number of observations 23 (riverflow), 50 (rainfall) and 61 (temperature). The possibility of "artificial predictability" was initially quite large for the riverflow calibration. However, the reduction in the number of predictor variables through the use of principal component analysis considerably reduced the likelihood of "artificial predictability". The number of predictor variables actually used here ranged from three to seven. If "artificial predictability" still remained this should have become apparent during verification.

7.4 VERIFICATION

Verification is necessary to establish the reliability of the calibration. It is easy to over-fit the calibration data so that the calibration appears successful but does not accurately reflect conditions outside the calibration period; "artificial predictability" (see above). It is therefore necessary to reserve some independent data (not used in calibration) for verification. A number of statistical verification tests can be used (Fritts et al. 1979, Gordon 1982) and in transfer function analysis, historical data and proxy climate records can also be used.

Statistical verification tests involve applying the regression equation developed for the calibration period to an independent predictor data set and comparing the estimated predictand with the actual predictand for the independent period. Subsample replication was used here where possible. The calibration data was divided in half and the regression undertaken for the first half and verified for the

second half. The roles for the two halves were then reversed and a regression carried out for the second half and verified on the first. The results can then be compared. There are several variations of this method (see Gordon 1982). The above method was used here for the temperature reconstructions as a large data set was available. However, for the rainfall and riverflow reconstructions, and for the response functions, this was not possible because of small data sets. Verification was undertaken on what independent data was available after ensuring the calibration data set was of adequate size. Two methods used to compare the estimated and actual predictands are the correlation coefficient (r) and reduction of error statistic (RE). The correlation coefficient is easily used and takes into account the number of cases of agreement and disagreement between variables and the relative degree of correspondence. The correlation coefficient was described in Chapter 4.

A more rigorous verification test is the RE statistic (Fritts 1976, Fritts et al. 1979) which is computed as,

$$RE = 1 - \frac{(Y_t - \hat{Y}_t)^2}{(Y_t - \bar{Y})^2}$$

where Y is the observed value and $\hat{Y}$ the estimated value for year t; $\bar{Y}$ is the mean value for the calibration period. RE differs from the correlation coefficient in that it accounts for the position of the calibration mean relative to the observed and estimated values (Fritts et al. 1979). This statistic can be strongly affected by only a few poor estimates with a resultant negative RE value. Because RE is highly sensitive to differences between the observed and estimated values, any positive RE value is considered encouraging (Fritts 1976).

In transfer function analysis, historical records and other proxy records of past climate can also be used to verify the reconstruction.

CHAPTER EIGHT

RESPONSE FUNCTION ANALYSIS

8.1 INTRODUCTION

In this chapter, response functions for the chronologies developed here and also for those developed by LaMarche et al. (1979c) in the South Island, are presented. The different chronology groups are first considered separately and then compared at the end of the chapter. These are the first response functions developed using principal component multiple regression techniques, to be presented for New Zealand tree-ring chronologies. Response function analysis is used here to identify the climatic factors influencing tree growth, rather than to reconstruct past climates. It is essentially a means of characterising the climatic response of different tree-ring chronology groups. In Chapter 9 the derived response functions are used as an aid in selecting suitable tree-ring chronologies for palaeoclimatic reconstruction.

Interpretation of response functions can be problematic as although a regression coefficient (also called a response function element or weight) may be statistically significant (at the 95% level) it does not necessarily imply a cause-and-effect relationship between climate and tree growth; by chance three out of twenty four regression coefficients can be expected to be significant (at the 95% level) in each response function (Gray et al. 1981). Isolated significant regression coefficients must be treated with caution. Coefficients that show distinct trends (e.g. positive for several months) and are common to several response functions from similar chronologies (e.g. timberline *Nothofagus solandri* chronologies), are more amenable to biological interpretation.

8.2 PSEUDO-CHRONOLOGY

A pseudo-chronology (RANDOM) developed from random numbers (see Section 6.5) is used to help interpret the response functions. I am aware of only one other example of the use of randomised tree-ring chronologies for evaluating response functions (Cropper 1982b). Although only 26% of the variance is explained by climate and no variance is explained by prior growth here (Table 8.1), the presence of distinct

trends amongst the coefficients (Fig. 8.1) highlights the need for caution in interpreting response functions. The non-significant verification (Table 8.1) shows that the developed regression equation does not apply outside the calibration period.

TABLE 8.1 Summarised results for the pseudo-chronology response function.

Calibration and verification statistics						
	K	r_T^2	r_C^2	r_P^2	r_V^2	RE
RANDOM	4	0.26	0.26	0.00	-0.06	-0.20

(See Table 8.2 for explanation of abbreviations)

The ability to explain 26% of the variance in the RANDOM chronology suggests that response functions explaining low amounts of variance due to climate need judicious interpretation. The apparent trends in the RANDOM response function can be interpreted in terms of a temperature limitation of growth at the start of the growing season and a rainfall limitation later; biologically a plausible explanation. However, if further RANDOM response functions were developed they would not be expected to show the same pattern of regression coefficients. Because of problems in verification of the other response functions developed here (see Section 8.8.1), the occurrence of similar response functions for different chronologies is considered evidence for some reliability in the response functions.

8.3 *LIBOCEDRUS BIDWILLII*

Response functions for the six South Island *Libocedrus bidwillii* chronologies are presented in Fig. 8.2 and relevant statistics summarised in Table 8.2.

8.3.1 AHA189 (Grey River Valley, Westland)

Climate accounts for 12% of the variance in the AHA chronology and prior growth 13% (Table 8.2). No obvious trends are present in the response function (Fig. 8.2), although temperature and rainfall do tend to be of opposite sign. Temperature tends to be positively associated

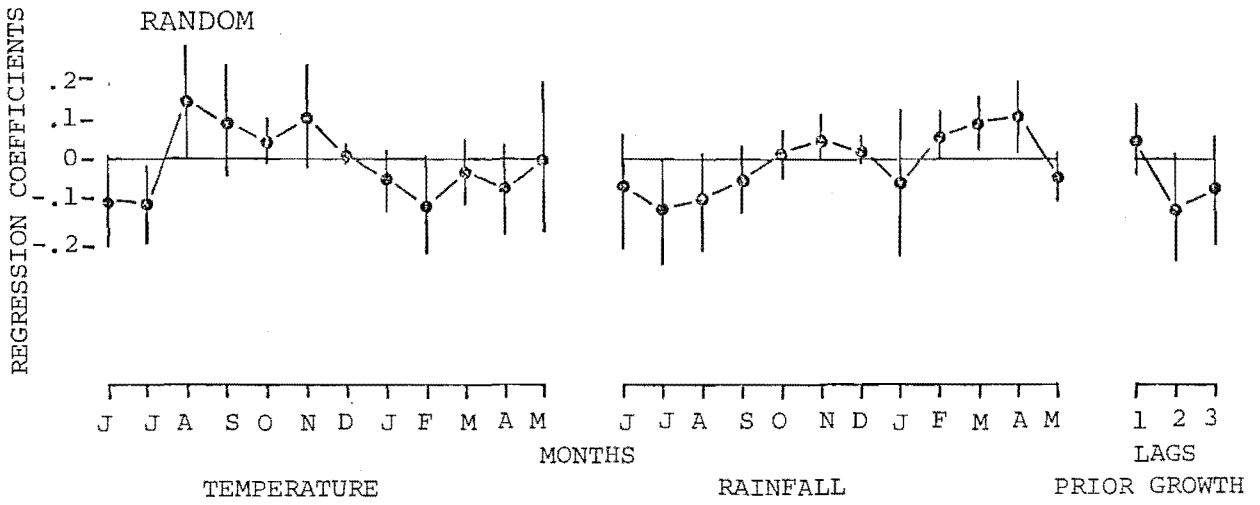


Figure 8.1 Pseudo-chronology response function.

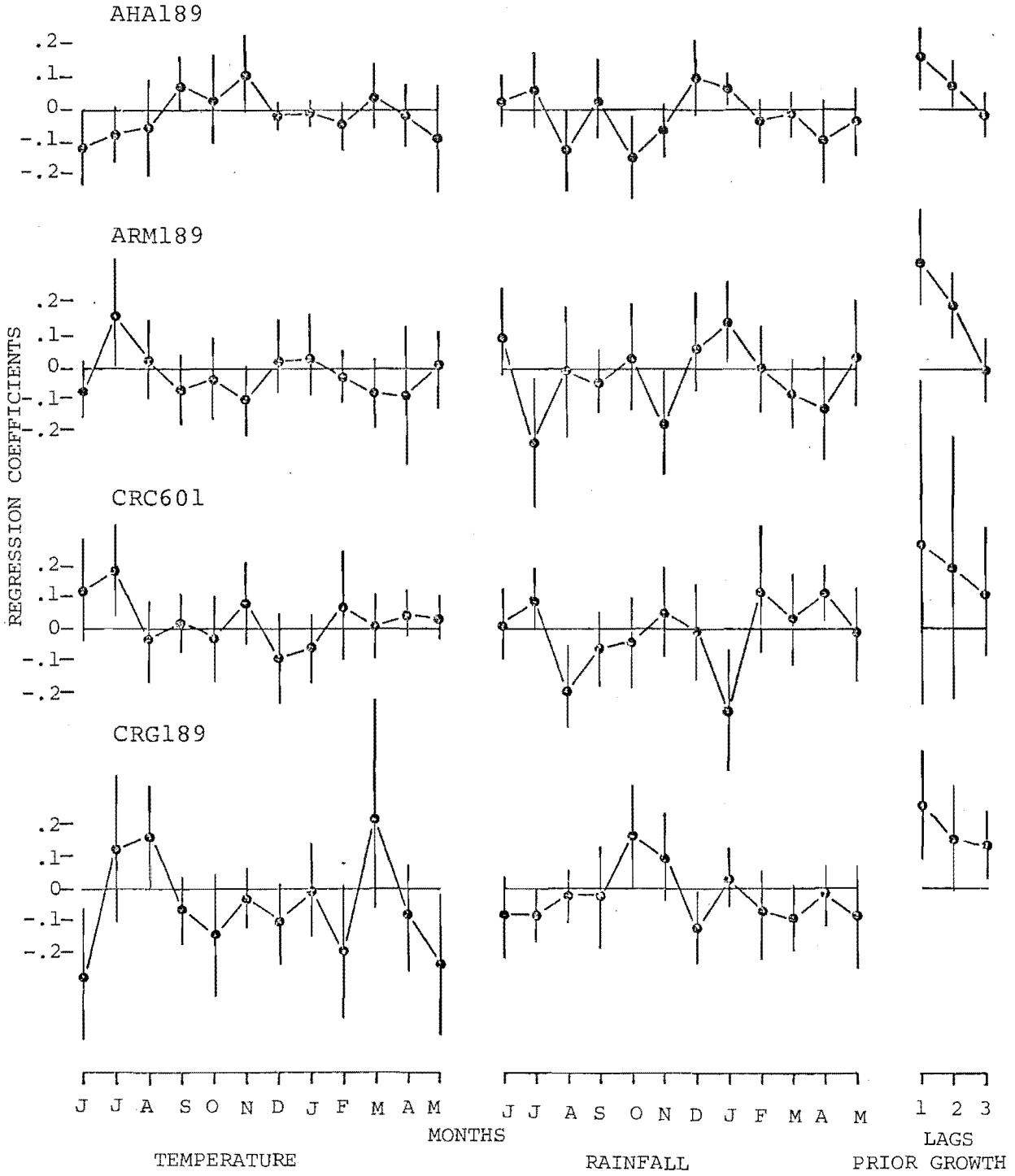


Figure 8.2 *Libocedrus bidwillii* response functions.

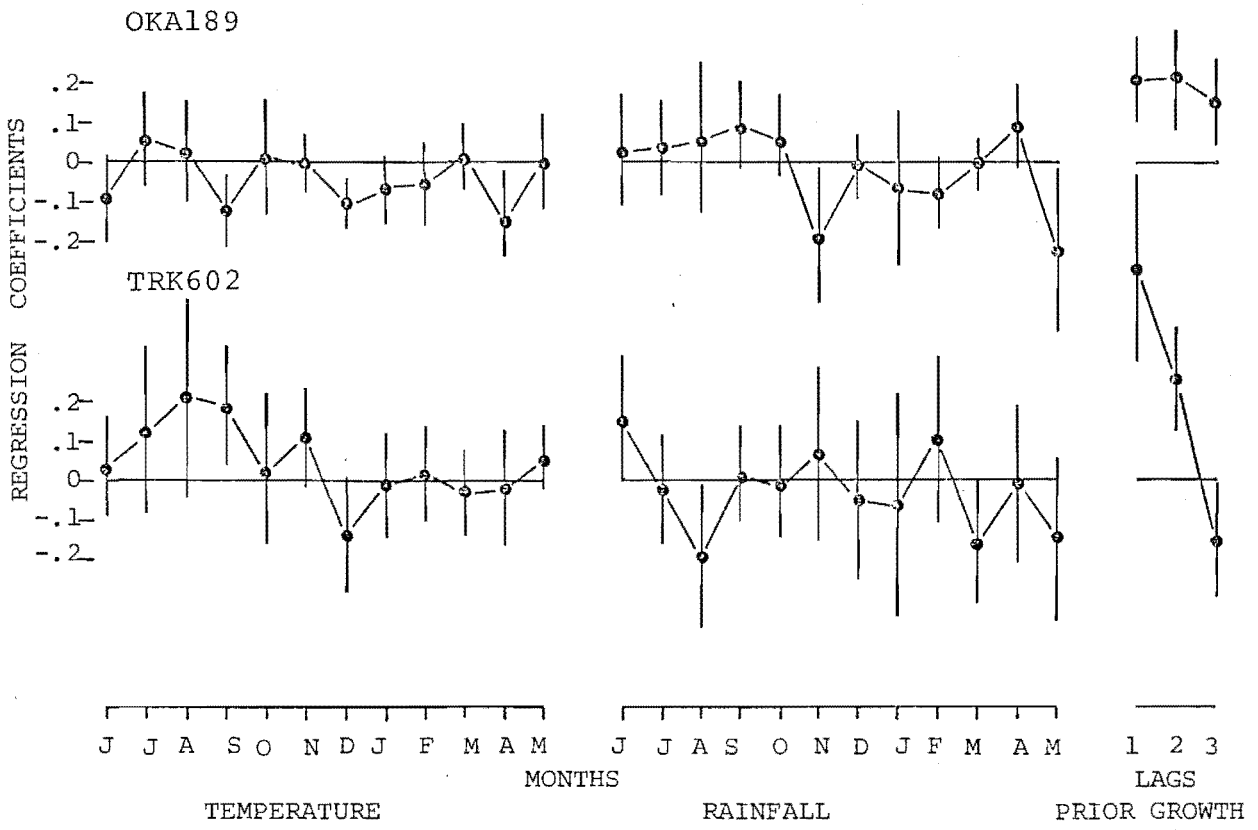


Figure 8.2 continued.

TABLE 8.2 Summarised results for the six *Libocedrus bidwillii* chronology response functions.

Calibration and verification statistics

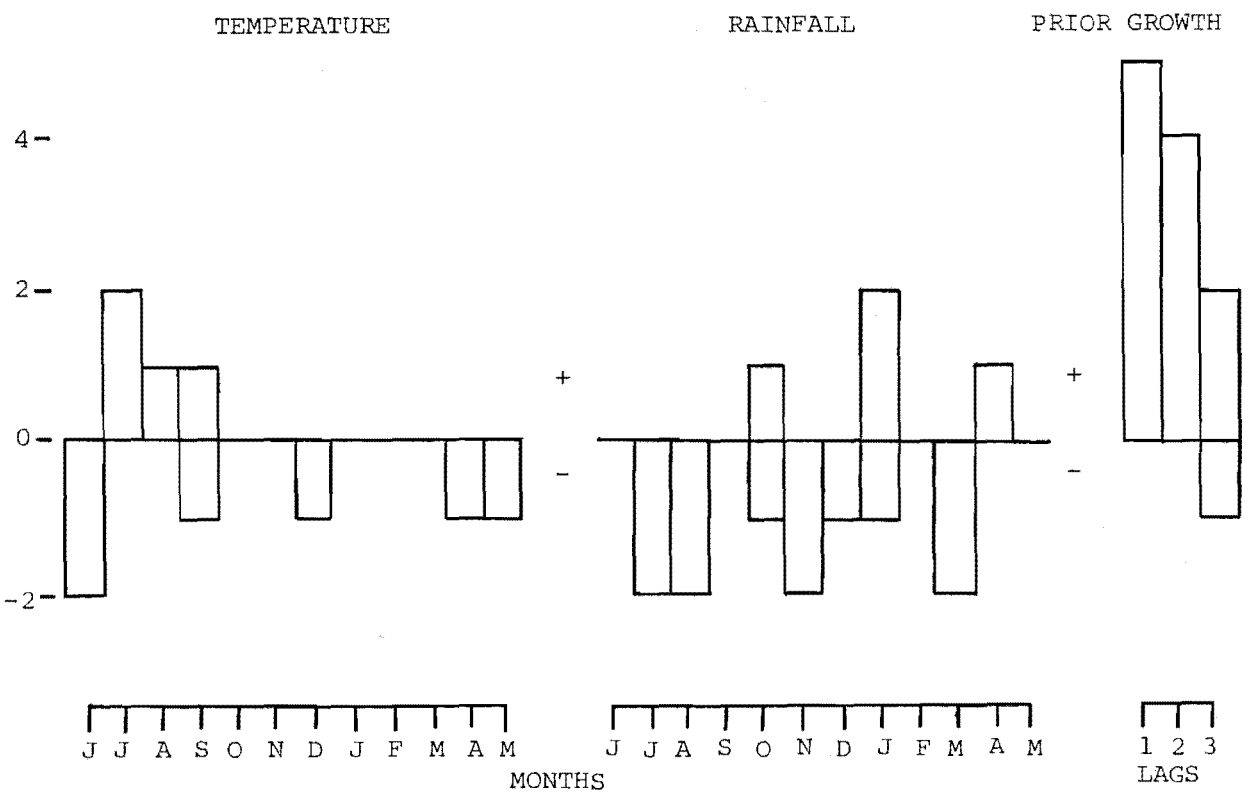
	K	r_T^2	r_c^2	r_p^2	r_v^2	RE
AHA189	5	0.25	0.12	0.13	0.53	+0.39
ARM189	7	0.51	0.19	0.32	0.06	+0.39
CRC601	7	0.58	0.25	0.33	0.11	-1.51
CRG189	7	0.63	0.35	0.28	0.03	-0.12
OKA189	6	0.60	0.33	0.27	0.00	-0.31
TRK602	9	0.61	0.14	0.47	0.37	+0.23

K-number of principal components entering regression; r_T^2 - total variance explained; r_c^2 - variance due to climate; r_p^2 - variance due to prior growth; r_v^2 - variance explained in verification; RE - reduction of error.

Distribution of significant regression coefficients

	TEMPERATURE												RAINFALL												PRIOR GROWTH		
	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	1	2	3
AHA189	-																-			+					+	+	
ARM189		+												-				-		+					+	+	
CRC601		+													-				-			+					
CRG189	-		+								-			-			+		-						+		+
OKA189				-			-			-												-			+	+	+
TRK602				+											-							-			+	+	-

Number of significant coefficients



with growth in spring and early summer and rainfall is significantly negative in October. Rainfall is positive in December and is significantly positive in January. Prior growth at lags of both 1 and 2 years is also significant. Autocorrelation is high in the chronology; 0.77 for the whole chronology and 0.58 for the calibration period.

8.3.2 ARM189 (Banks Peninsula, Canterbury)

This chronology was initially developed by LaMarche et al. (1979c). Two tree-ring series from a further tree were incorporated here (see Section 5.5.2). Two response functions were determined (Fig. 8.3); one for the period 1920-1958 using the original chronology and the second for the period 1930-1977 using the revised chronology. 58% of the variance in the first response function is explained by climate and 17% by prior growth, while only 19% in the second is due to climate and 32% to prior growth. The shape of the response functions are similar ($r=0.61$, $P < 0.05$), but only one significant element (July temperature) matches. Interpretation of these response functions is not easy but rainfall appears more important than temperature. Correlation coefficients show the rainfall response to be more similar ($r=0.66$, $P < 0.05$) than the temperature response ($r=0.50$, $P < 0.05$).

8.3.3 CRC601 and TRK602 (Whitcombe River Valley, Westland)

These chronologies were developed from trees in adjacent stands and similarities occur between their response functions ($r=0.46$, $P < 0.05$). Both have low variance attributable to climate (25% and 14%) and considerable variance attributable to prior growth (33% and 47%, Table 8.2). The temperature responses have some similarities and are largely positive (Fig. 8.2). Positive associations with late winter temperature occur (July significant, CRC; September significant, TRK) and simple correlation coefficients between temperature and tree growth are also positive from June to November (Table 8.3). Rainfall responses are less clear and commonly negative.

TABLE 8.3 Correlation coefficients between temperature and the CRC601 and TRK602 tree-ring chronologies

	J	J	A	S	O	N	D
CRC	0.06	0.37	0.01	0.13	0.09	0.13	-0.09
TRK	0.09	0.27	0.01	0.14	0.14	0.07	-0.02

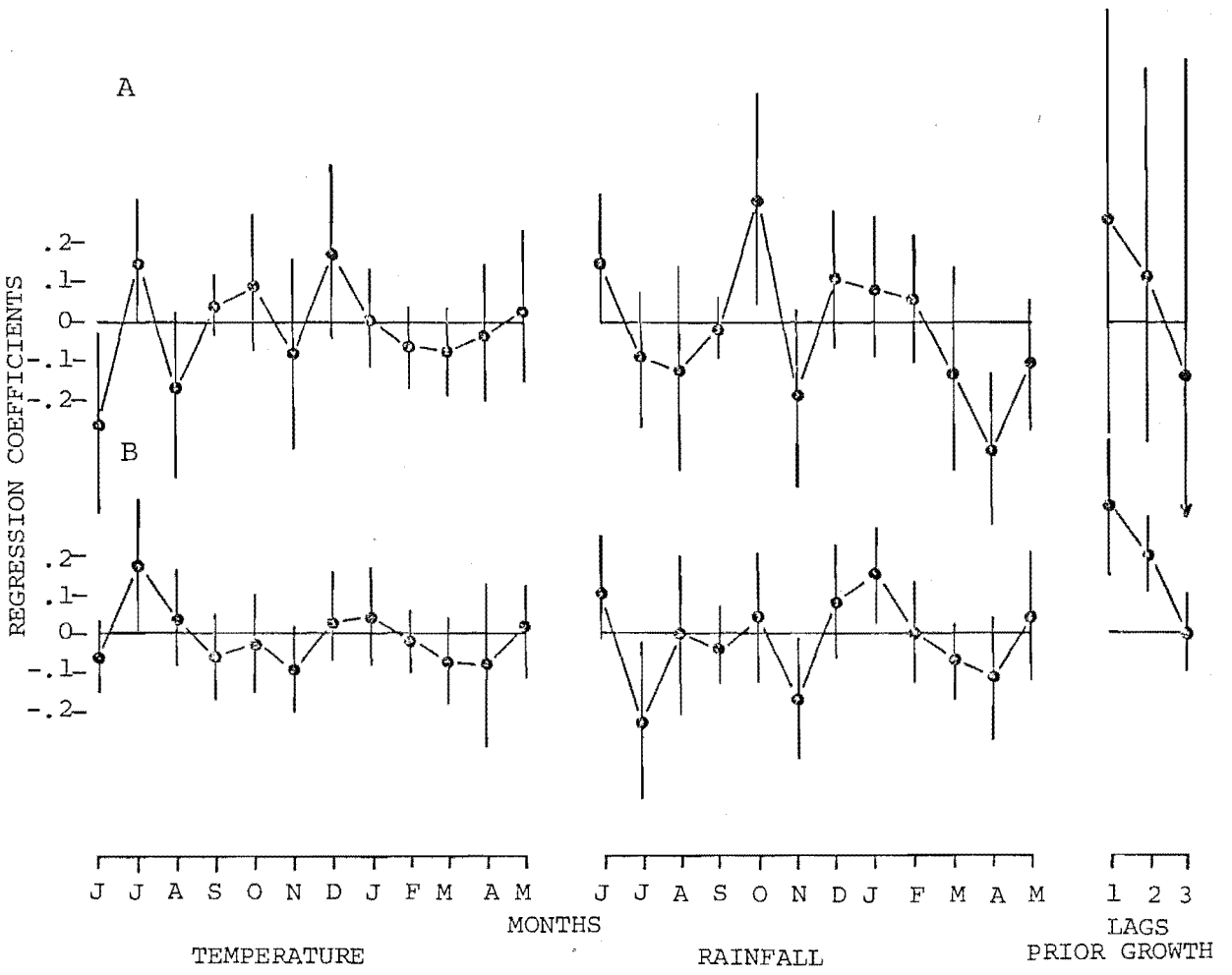


Figure 8.3 Response function for original ARM189 chronology (A) and for the revised version (B).

8.3.4 CRG189 and OKA189 (Dunedin, Otago and Catlins Range, Southland)

Variance explained by climate in the response functions for these two chronologies is similar, accounting for 35% in CRG and 33% in OKA (Table 8.2). Prior growth accounts for a further 28% and 27% respectively. The response functions show few clear patterns, and are therefore not easy to interpret (Fig. 8.2). In the CRG response function, significant temperature associations occur in August (positive) and June and May (negative). A significant positive rainfall association occurs in October and negative ones in July and December. The OKA response function has significant negative associations with temperature in September, December and April and significant negative associations with rainfall in November and May. At both sites, temperature associations tend to be negative for most of the year, while rainfall associations are more variable.

8.3.5 Discussion

The low amount of variance explained by climate and the lack of trends common to all six *Libocedrus bidwillii* response functions makes their interpretation speculative. The lack of agreement between the sites could be due to ecological differences. However, the overall poor relationship with climate (c.f. *Nothofagus* response functions) suggests that the techniques used and climatic parameters investigated may not be the most appropriate for the *L.bidwillii* chronologies.

The pronounced difference between the two ARM response functions (Section 8.3.2) is probably related to the differing composition of the two versions of the ARM chronology used. In the second response function (1930-1977), the tree-ring data is derived from one tree only for the period 1959-1977. In Section 6.6.2 it was suggested that large sample sizes helped enhance the common climatic signal while reducing non-climatic "noise". It is likely that the climatic signal in the one tree is less clear than in the combined ARM chronology. The low explained variance attributable to climate and high explained variance attributable to prior growth could then reflect the influence of the tree record from the single tree.

The similarity between the trends in the two response functions does suggest the possibility of a link between tree growth and climate. The positive association with growing season rainfall is prominent. However, the use of a climatic parameter such as evapotranspiration may

be more appropriate than rainfall or temperature in evaluating this link further.

Variance due to prior growth accounts for a large proportion of the total explained variance in all six *Libocedrus bidwillii* response functions and is, proportionally, considerably greater than for the *Nothofagus* chronology groups. Prior growth in *L.bidwillii* has been discussed in Section 6.2. The techniques used to develop the response functions may well be unable to separate out the influence of prior growth from that of direct climatic influences. Modified response function techniques may be more appropriate for studying the growth-climate relationship in these strongly autocorrelated chronologies. The use of de-autocorrelation techniques (Guiot et al. 1982, Wigley and Lough unpublished manuscript) and spectral analysis (LaMarche 1974b, Guiot et al. 1982) may improve the calibrations.

Alternatively, it may be more appropriate to examine climatic factors other than mean temperature and total rainfall. It has been suggested that solar radiation levels influence tree growth in the Pacific North West of North America and in Tasmania (Val LaMarche personal communication 17 December 1982). Benecke and Havranek (1980b) showed that at temperatures below 14^{o}C, solar radiation becomes the main limiting factor for *Nothofagus solandri* photosynthesis in the Craigieburn Range.

An earlier analysis of the CRC and TRK chronologies (Norton 1980b) found that sunshine levels during the growing season were significantly correlated with ring width. Correlation coefficients between a combined CRC and TRK tree-ring series and Hokitika sunshine are presented in Fig. 8.4 and show a significant correlation with December sunshine and near significant correlations from November to March. A correlation with mean November to March sunshine is also highly significant ($P < 0.05$).

The predominance of positive correlations with sunshine suggests a direct relationship between tree growth and solar radiation. The rate of photosynthesis is directly dependent on incident light intensity and this can be limiting at low levels (Tranquillini 1979, Benecke and Havranek 1980b). Net photosynthesis in young *Pinus cembra* trees at timberline in Austria started to decline when daily solar radiation dropped below 19% of the maximum possible solar radiation. This rather

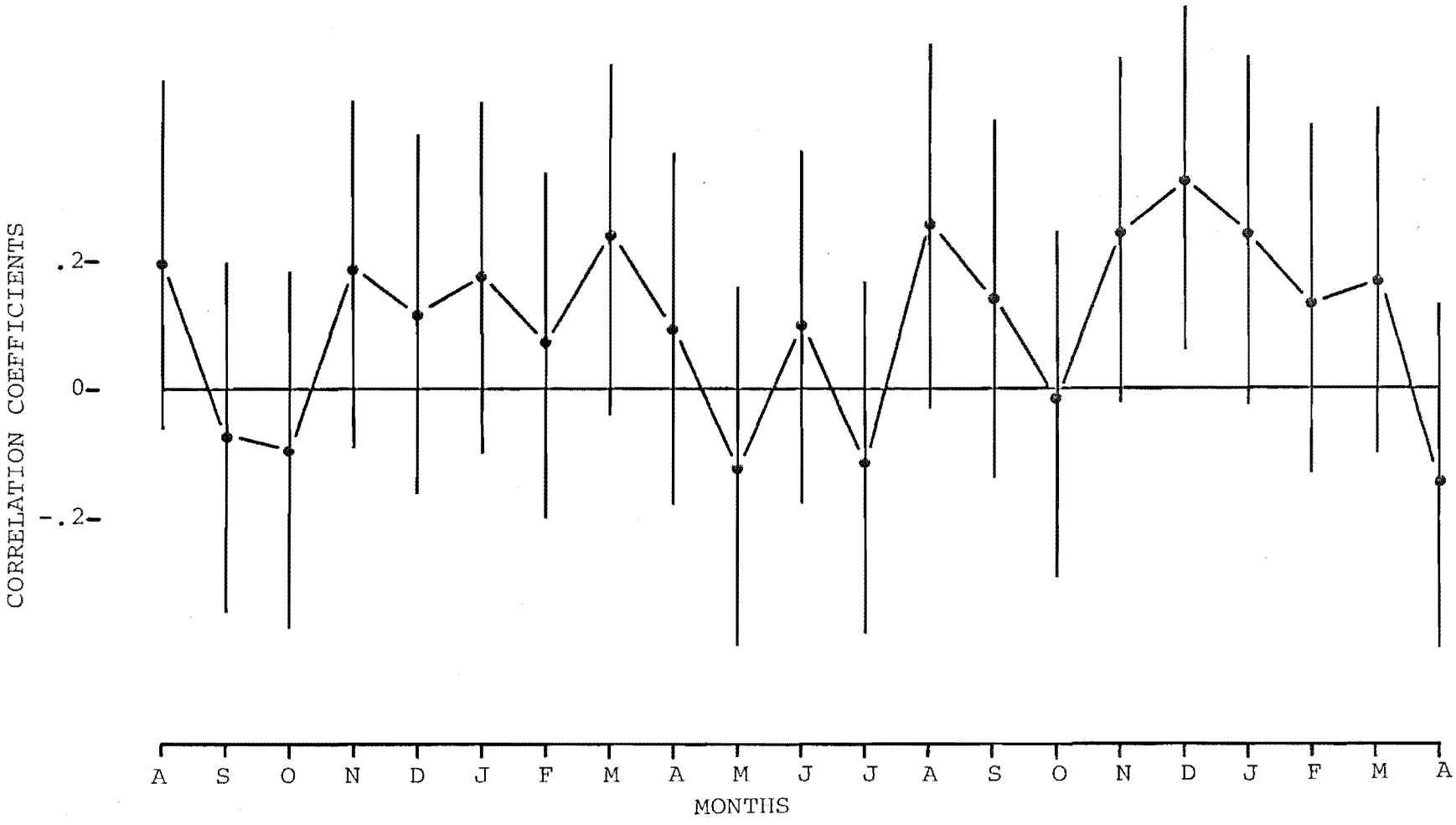


Figure 8.4 Correlation coefficients between Hokitika sunshine for a 21 month period and the combined CRC and TRK chronologies.

low threshold level was not attained on 14% of all days during a five month period over the growing season (Tranquillini 1979). During December 1970 and January 1971, solar radiation levels at the Ivory Glacier (7 km to the southwest of the CRC and TRK sites) did not rise above 20% of the maximum daily solar radiation recorded for this period (784.1 ly) on 23% of the days (Anderton and Chinn 1973).

Clouds, on average, absorb and reflect 53% of the incident solar radiation (Larcher 1975). Cloudiness is common at the CRC and TRK sites and even in years of decreased cloudiness, a large number of days receive light levels presumably well below those required for adequate photosynthesis. A decrease in the amount of available solar radiation during years with above-average cloud cover, could reduce photosynthesis and dry matter production of *Libocedrus bidwillii*, with narrow growth rings being formed.

The possibility of this type of relationship occurring illustrates the need to consider climatic factors other than mean temperature and total rainfall. However, the lack of good records is a problem that is difficult to overcome. Although a long (48 year) sunshine record is used here, its relevance to the CRC and TRK sites is uncertain because of the very pronounced microclimate differences occurring in Westland (Hessell 1982). The sunshine record is for Hokitika (39 m a.s.l.), a coastal town 40 km to the north of the tree-ring sites (at about 900 m a.s.l.) and separated from it by a 2000 m mountain range and a 20 km wide coastal plain. It is common to see this plain cloud covered and the mountains cloud free or vice versa.

The climate at both the CRG and OKA chronology sites is dominated by southerly winds with a high incidence of fog and low cloud (P. Wardle and Mark 1956, Johnson et al. 1977). Solar radiation may be an important influence on tree growth here also.

At present the relationships between *Libocedrus bidwillii* growth and climate are only poorly understood. Considerably more research is needed before these can be interpreted more fully.

8.4 *NOTHOFAGUS MENZIESII*

Response functions for the five *Nothofagus menziesii* chronologies are presented in Fig. 8.5. There are some small differences but the

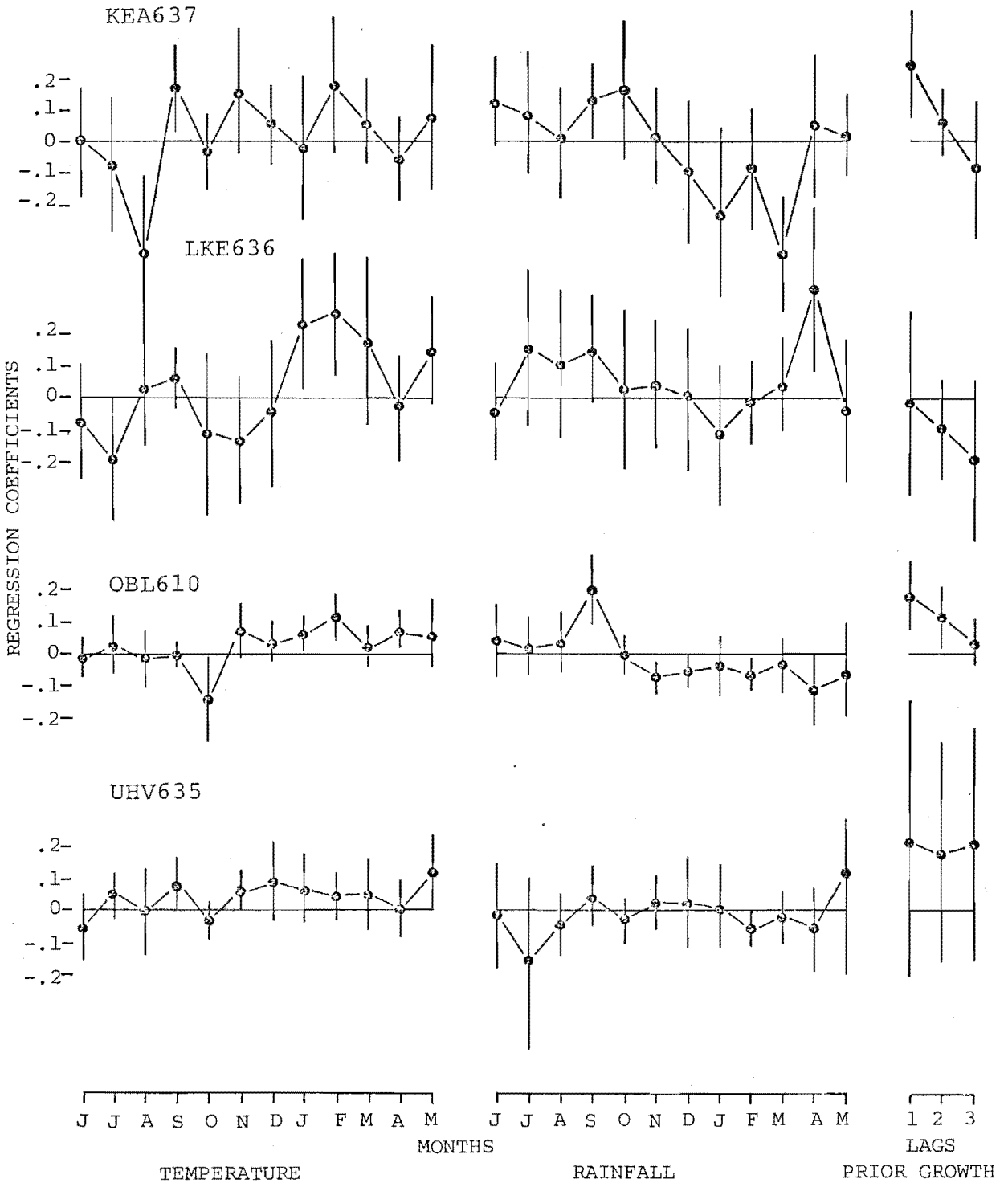


Figure 8.5 *Nothofagus menziesii* response functions.

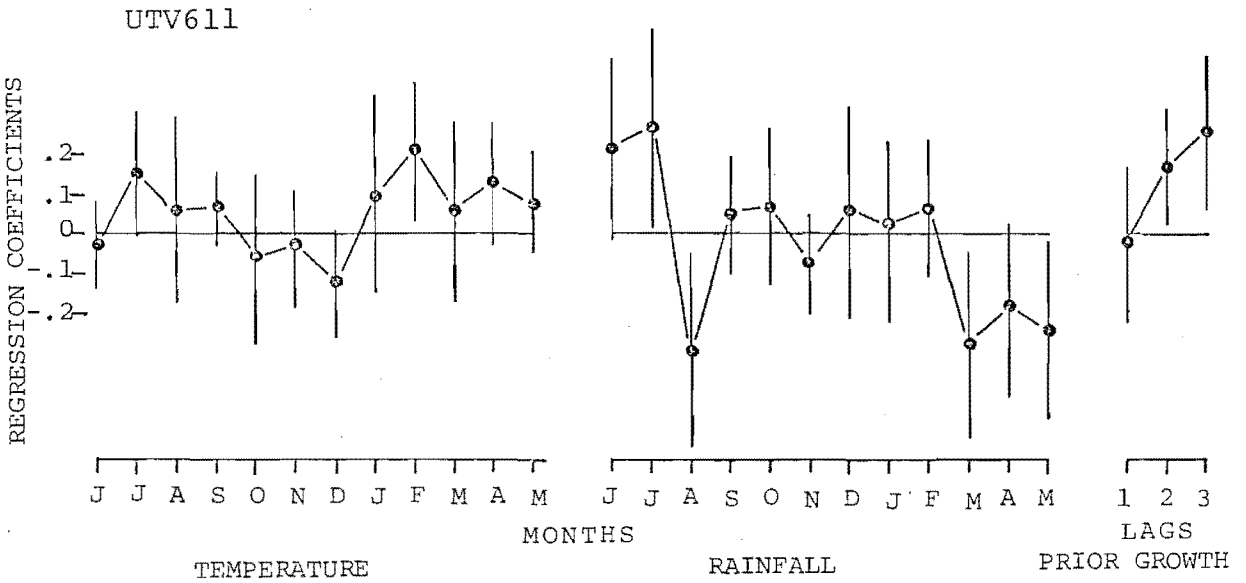


Figure 8.5 continued.

five chronologies have many similarities and are treated together. Except for UHV, the ratio of climate explained variance to prior growth explained variance is about 7:1 (Table 8.4). Variance explained by climate ranges from 34% to 54%, while that explained by prior growth ranges from 0% to 9%. The UHV response function is atypical with only 17% of the variance explained by climate and 47% by prior growth. Trees at this site are largely young and even-aged. Low climate explained variance could reflect continued growth and competition between trees at this site. However, the distribution of positive and negative response function weights is similar to the other response functions, suggesting that climate is influencing growth in a similar way.

The response functions show similar trends. Temperature regression coefficients are positive during the growing season (December to March) and are otherwise more variable. Rainfall regression coefficients are more variable but tend to be negative during the growing season. The summarised results (Table 8.4) show 10 of the 12 significant temperature coefficients as positive and 7 of the 10 significant rainfall coefficients as negative. This type of relationship is typical of response functions for trees growing near the alpine timberline (e.g. Schweingruber et al. 1978) or near the arctic tree line (e.g. Jacoby and Cook 1981, Kuivinen and Lawson 1982). A positive relationship with temperature during the growing season reflects the occurrence of low summer temperatures which limit photosynthesis and other physiological processes necessary for radial growth (Fritts 1976). Radial growth at Lake Eyles (LKE) occurred mainly in January to March during the 1981-1982 growing season (Chapter 2) and correlates well with the time when the temperature regression coefficients are positive. Similar response functions occur for near timberline *Nothofagus solandri* chronologies. The relationship between summer temperature and tree growth is discussed more fully in Section 8.6.1.

8.5 *NOTHOFAGUS SOLANDRI* ALTITUDINAL TRANSECT

In Section 5.4 it was shown that the most sensitive trees in *Nothofagus solandri* forests grow close to the alpine timberline. It was suggested that at these sites climate strongly influenced tree growth and that these trees would be the most useful for climatic analysis. Response functions for the seven tree-ring chronologies discussed in

TABLE 8.4 Summarised results for the five *Nothofagus menziesii* chronology response functions.

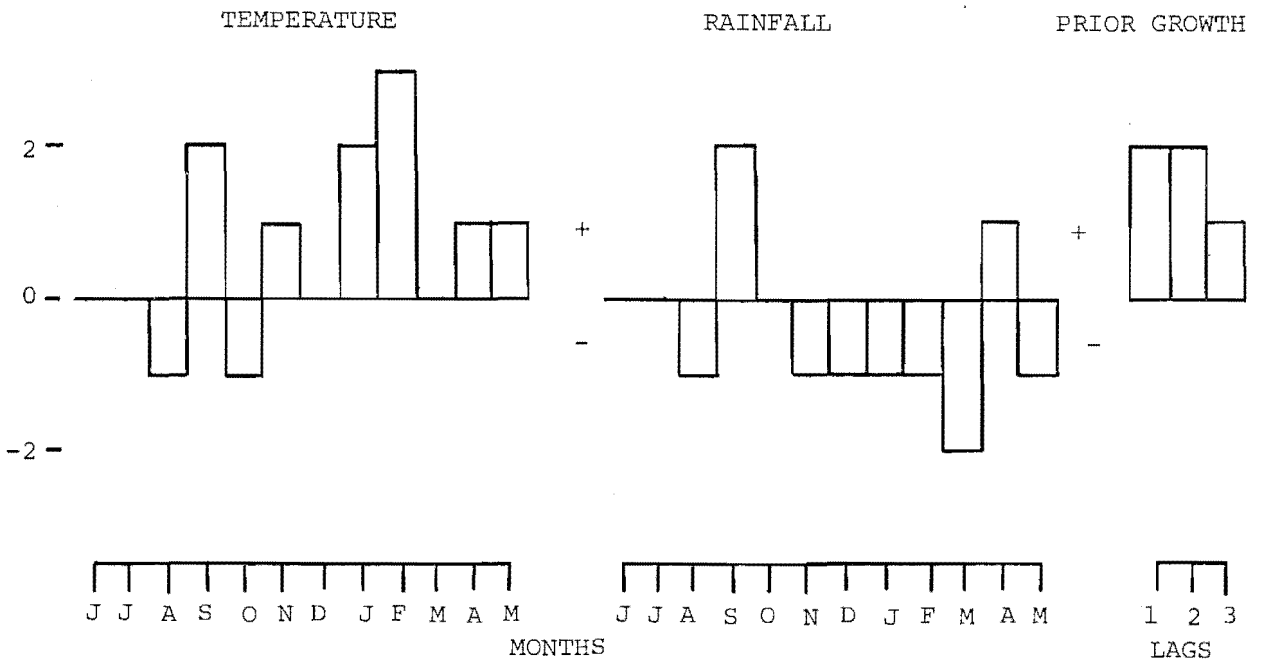
Calibration and verification statistics

	K	r^2_T	r^2_c	r^2_p	r^2_v	RE
KEA637	10	0.61	0.54	0.07	0.00	-1.10
LKE636	9	0.44	0.44	0.00	0.03	-0.32
OBL610	5	0.40	0.34	0.06	0.04	+0.11
UHV635	5	0.64	0.17	0.47	0.04	-0.19
UTV611	8	0.44	0.35	0.09	0.16	+0.01

Distribution of significant regression coefficients

	TEMPERATURE												RAINFALL												PRIOR GROWTH		
	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	1	2	3
KEA637			-	+												+						-			+		
LKE636								+	+														+				
OBL610					-			+	+		+					+		-	-		-				+	+	
UHV635				+		+						+															
UTV611									+							-						-	-			+	+

Number of significant coefficients



Section 5.4 are presented in Fig. 8.6 and relevant statistics summarised in Table 8.5.

The total amount of variance explained in the response functions ranges from 57% to 66%, except for the highest altitude chronology (LGH617) which only explains 47% of the variance. This low value reflects a very low amount of variance explained by prior growth (11%). Variance explained by prior growth and climate, do, however, differ with altitude. Variance explained by prior growth increases, although somewhat irregularly, with decreasing altitude from 11% at timberline to 43% at the second lowest site (LGH622), paralleling a similar increase in autocorrelation with decreasing altitude (Fig. 5.9).

Variance explained by climate is inversely related to that explained by prior growth and decreases with decreasing altitude. This parallels the decrease in common variance (%Y) and mean sensitivity shown in Fig. 5.9. However, some anomalies occur. The lowest altitude chronology (LGH623) has a large amount of climate explained variance; mean sensitivity and common variance (%Y) were also greater at this site and it was suggested that there could be some temperature limitation of growth here (see below). The ratios of variance explained by climate to variance explained by prior growth decline with decreasing altitude (Table 8.5), from 3.5 at timberline (LGH617) to 0.4 at LGH622. Again LGH623 and LGH618 differ slightly.

Examination of the response functions reveals several trends (Fig. 8.6) which are now discussed.

8.5.1 LGH617 (1400 m)

The response function for this chronology shows a pronounced positive association with both temperature and rainfall (Fig. 8.6). Near timberline, shoot expansion and radial growth commence in November (Chapter 2) and the significant positive association with both temperature and rainfall at this time reflects the need for warm temperatures and plentiful soil moisture for commencement of growth.

Temperature elements remain positively associated with growth until February and rainfall elements until April. The control of temperature over growth is strong. Increased dry-matter production occurs during seasons with warmer temperatures (Tranquillini 1979).

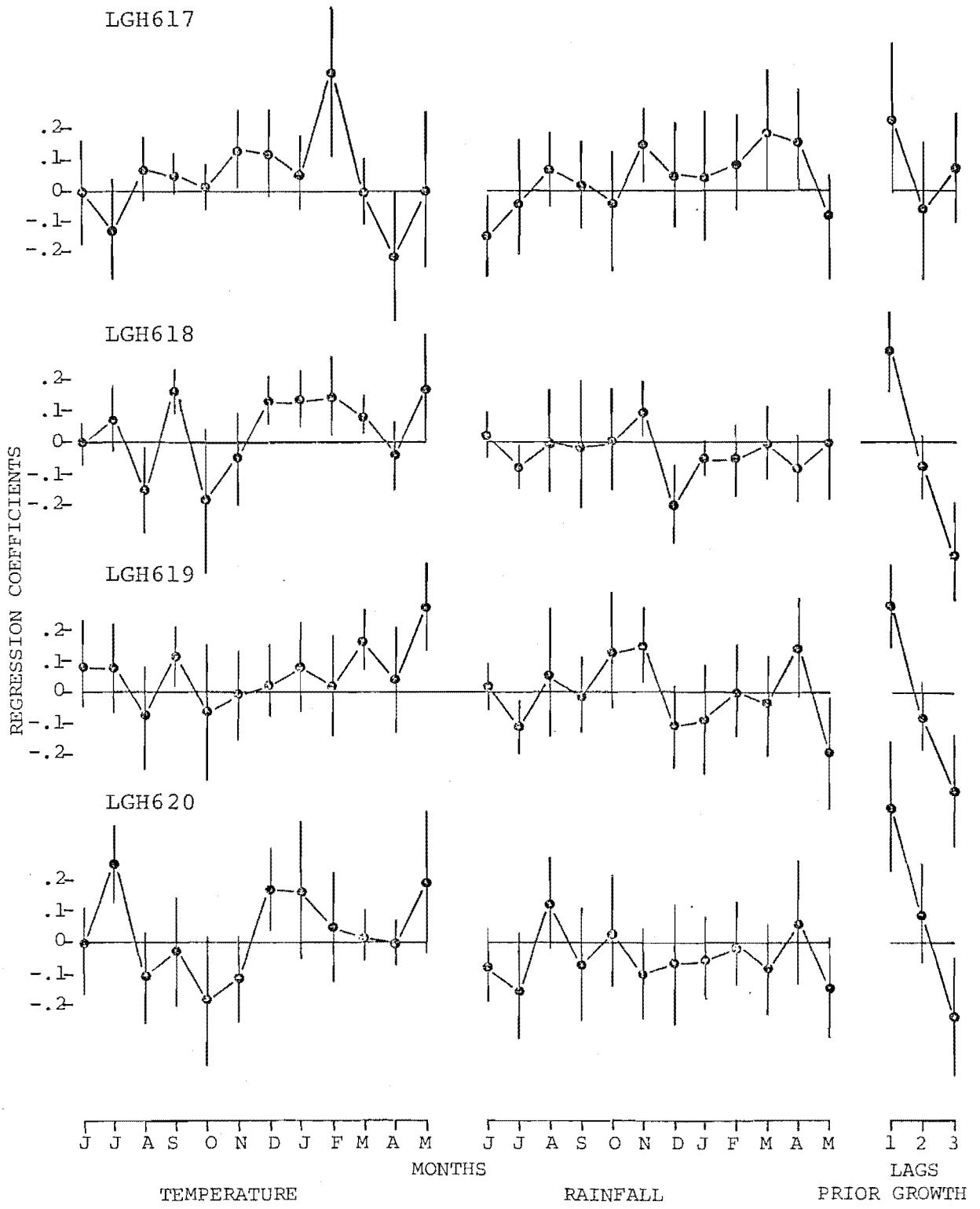


Figure 8.6 *Nothofagus solandri* altitudinal transect response functions.

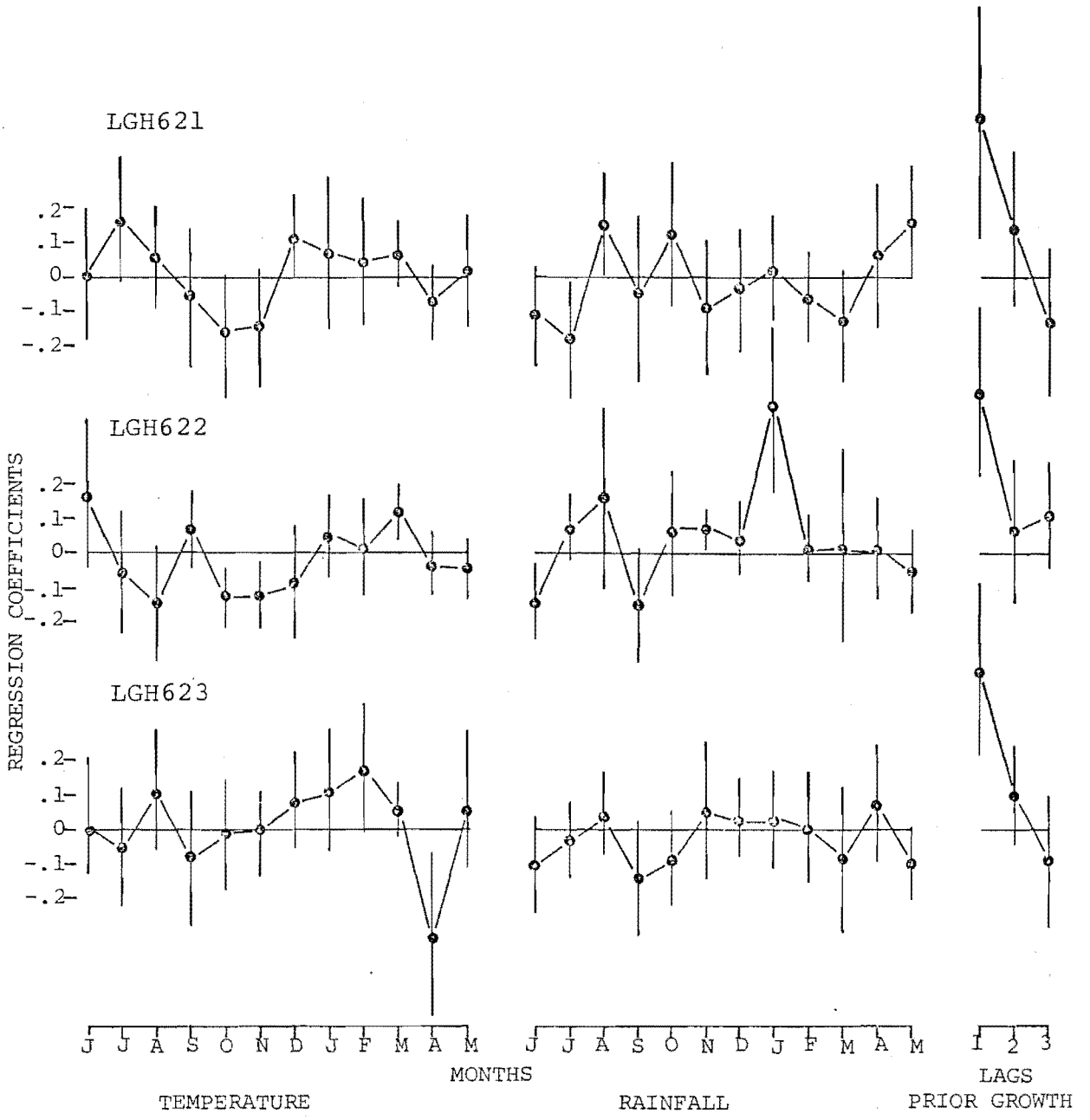


Figure 8.6 continued.

TABLE 8.5 Summarised results for the seven altitudinal transect *Nothofagus solandri* chronology response functions.

Calibration and verification statistics

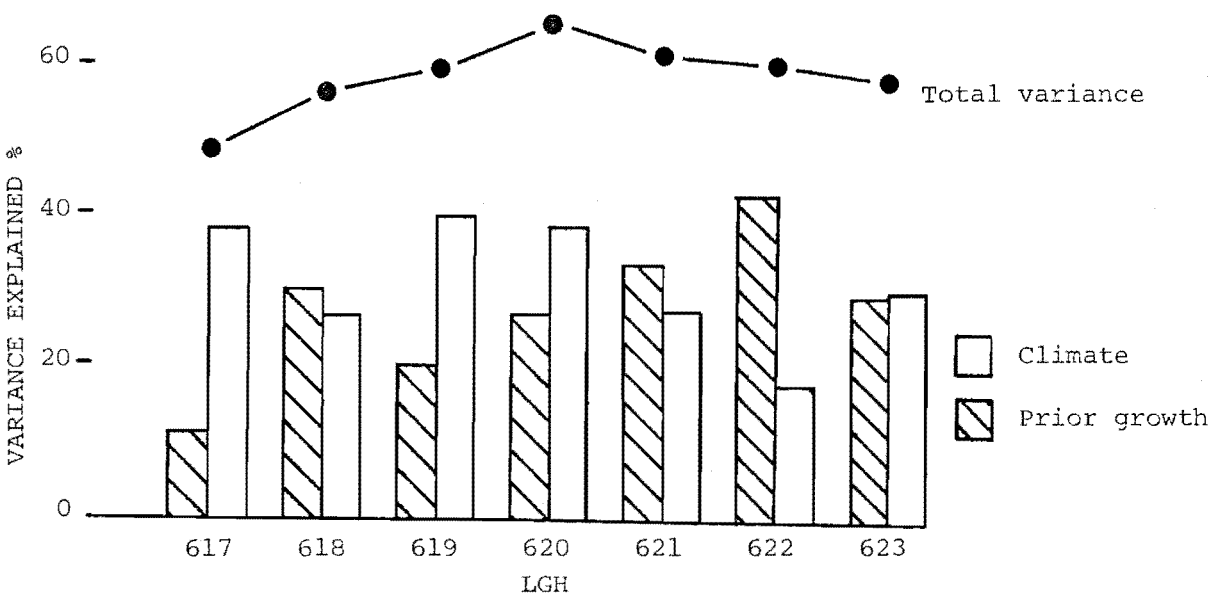
LGH	K	r_T^2	r_c^2	r_p^2	C/P	r_v^2	RE
617	8	0.49	0.38	0.11	3.5	0.03	-0.84
618	6	0.57	0.27	0.30	0.9	0.02	-0.72
619	8	0.60	0.40	0.20	2.0	0.01	-1.56
620	7	0.66	0.39	0.27	1.4	0.38	+0.07
621	9	0.62	0.28	0.34	0.8	0.11	+0.15
622	7	0.61	0.18	0.43	0.4	0.01	-0.89
623	9	0.59	0.30	0.29	1.0	0.35	+0.38

C/P - ratio of climate explained variance to prior growth explained variance

Distribution of significant regression coefficients

	TEMPERATURE												RAINFALL												PRIOR GROWTH		
LGH	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	1	2	3
617						+			+		−		−					+				+	+				
618			−	+			+	+	+	+				−				+	−						+		−
619				+						+		+		−				+						−	+		−
620		+					+							−										+	+		−
621														−	+										+		
622					−	−				+			−					+		+					+		
623											−														+		

Explained variance of the altitudinal transect chronologies



The significant positive rainfall elements in March and April and significant negative temperature elements in April suggest that rainfall (probably through soil moisture) limits growth towards the end of some growing seasons. Radial growth near timberline ceases in April-May (Chapter 2). It is likely that soil moisture at this time can have an important influence on the timing of growth cessation and hence total ring width. Located on a steep, rocky, north facing slope immediatley below a ridge crest, the site is susceptible to drought. These strong interactions with climate suggest that the trees are very sensitive to such effects. The low amount of variance explained by prior growth also indicates considerable year to year variation with little carry-over of climatic influence from previous years.

8.5.2 LGH618 (1300 m)

This response function is similar to those of other near timberline *Nothofagus solandri* chronologies (see Section 8.6.1) with significant positive temperature regression coefficients from December to March. Rainfall is significantly positively related to growth in November. Both warm temperatures and plentiful soil moisture seem necessary for the commencement of growth. The temperature coefficients remain significantly positive until March, indicating the importance of warm temperatures for biomass accumulation at these subalpine forest sites. Rainfall coefficients are variable suggesting that soil moisture is only rarely limiting to growth. Prior growth is important, being significant at a lag of one year (positive).

8.5.3 LGH619, 620 and 621 (1200 m, 1100 m and 1000 m)

The response functions for these chronologies are variable with few obvious trends present. A strong association with growing season temperature is not present, although some significant temperature coefficients occur (e.g. March in LGH619 and December in LGH620). A strong negative association with temperature in October and November in the LGH620 and LGH621 response functions could be related to seed development. In flowering years, warm temperatures at the time of flowering are likely to initiate seed development with a subsequent reduction in ring width because of shifts in resource allocation (see Section 6.7.3). During cool years flowers are aborted and seed development does not occur.

8.5.4 LGH622 (900 m)

It was noted in Section 5.4 that the LGH622 chronology differed from the other chronologies, having a low autocorrelation value and much slower mean growth rates. The suggestion that growth at this site could be limited by the availability of soil moisture is supported by the response function results as there are positive rainfall coefficients in 9 of the 12 months. November and January rainfall coefficients are significantly positive.

8.5.5 LGH623 (800 m)

This chronology was also noted in Section 5.4 as differing from the others. The site is on a valley floor terrace, adjacent to the Cass River, where, it was suggested, cold air drainage and frost could influence growth. Rainfall coefficients are all close to zero and the only significant climate coefficient is with April temperature (negative). The reasons for this are unclear. However, temperature coefficients for December to March are all positive and February and March nearly significant. This is similar to many of the near-timberline response functions (e.g. LGH618) and indicates the important influence of temperature on growth at this site.

8.6 *NOTHOFAGUS SOLANDRI*

8.6.1 Timberline chronologies

Sixteen *Nothofagus solandri* chronologies were developed from sites located close to the alpine timberline in Canterbury and Fiordland. The response of the trees to climate at all sites is broadly similar (Fig. 8.7). Variance explained by climate varies from 25% to 58% (mean of 41 ± 11%), and that explained by prior growth from 0% to 30% (mean of 10 ± 9%) (Table 8.6). The response function statistics are summarised in Fig. 8.8.

Response functions for timberline *Nothofagus solandri* chronologies have much in common with those from timberline *N.menziesii* chronologies, both in the amounts of variance explained by climate and prior growth and in the distribution of significant response function elements. Much of what is said below applies to the *N.menziesii* chronologies.

The relationship between ring width and late winter (June-August) temperature and rainfall is variable and could reflect chance correlations, rather than realistic biological responses.

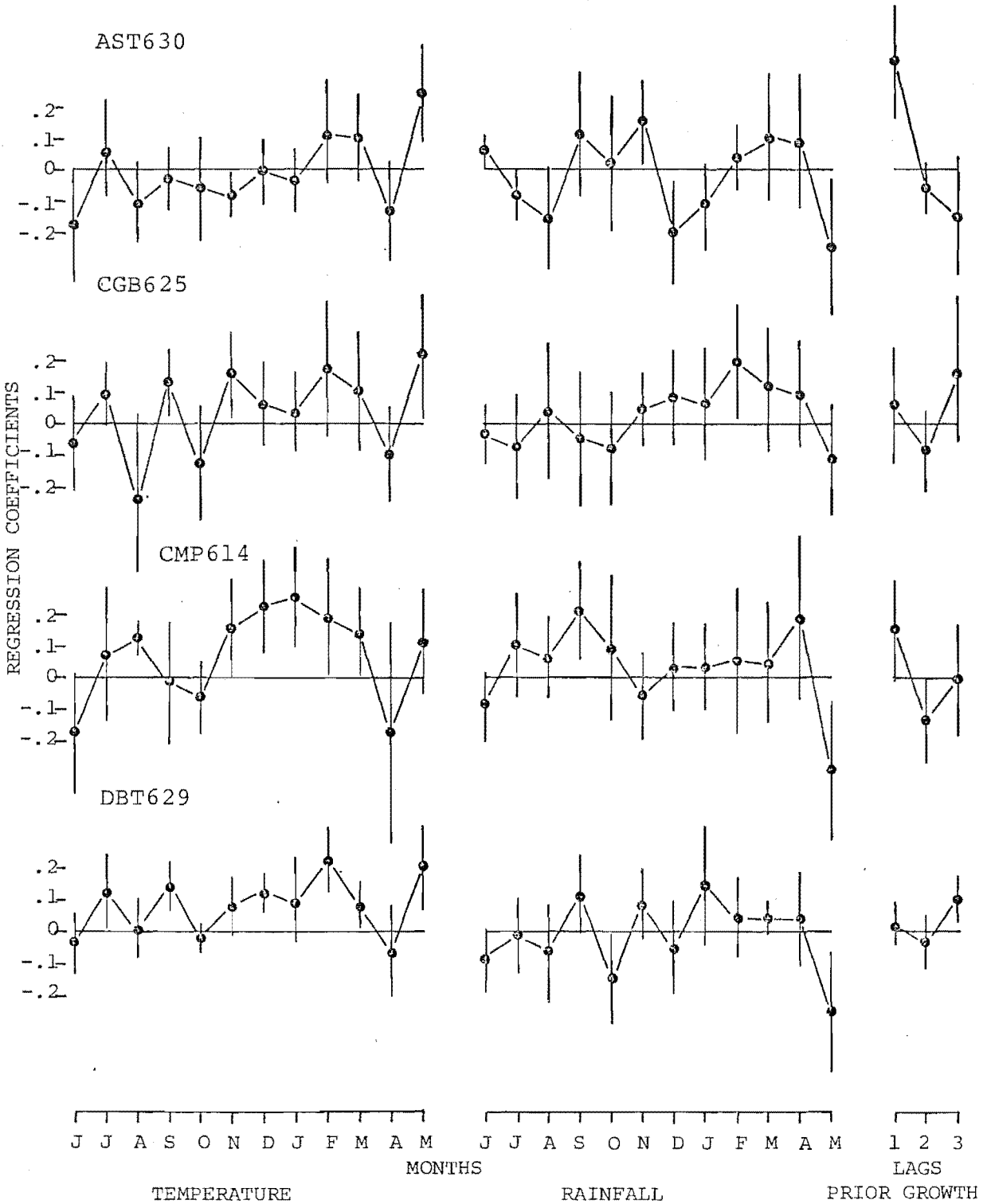


Figure 8.7 *Nothofagus solandri* (timberline) response functions.

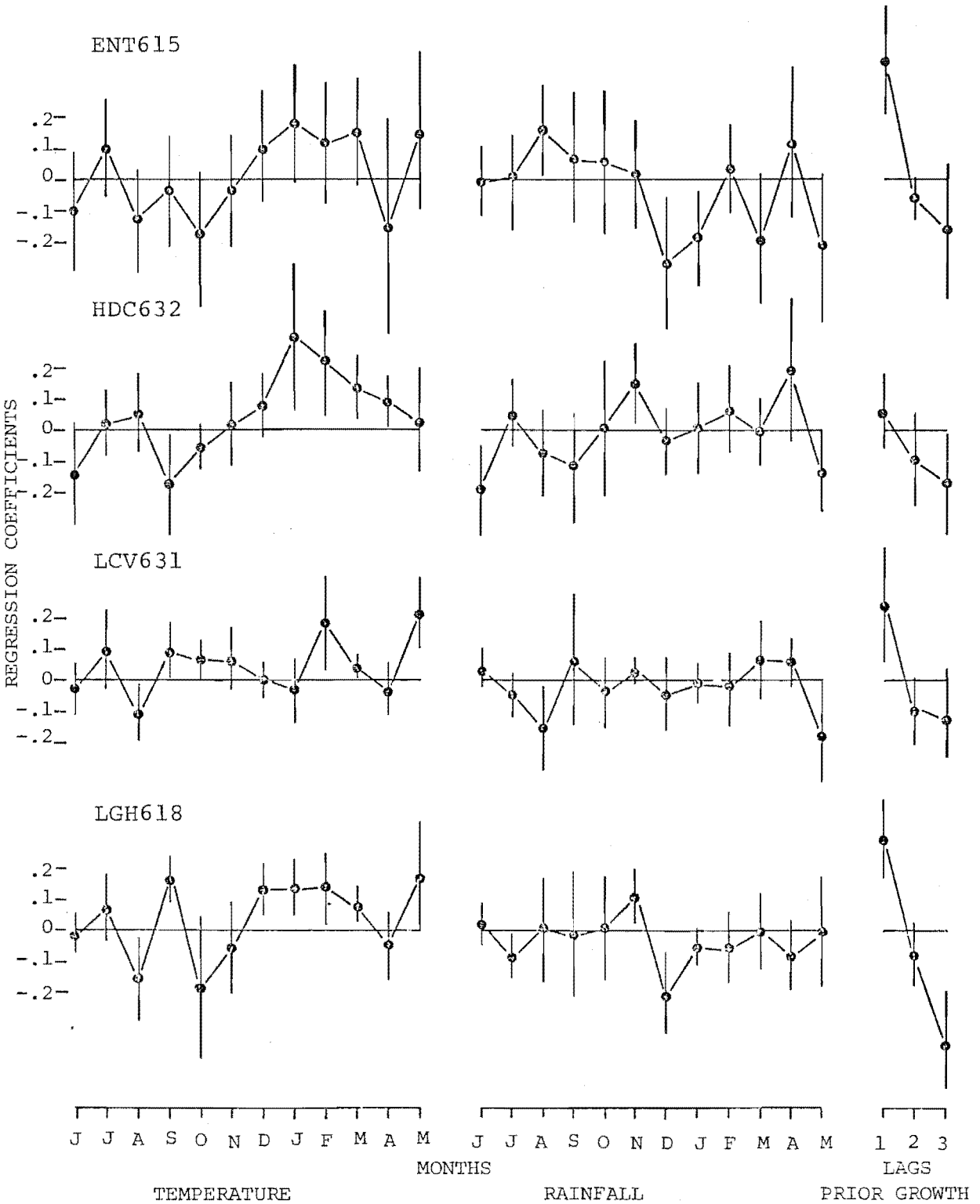


Figure 8.7 continued.

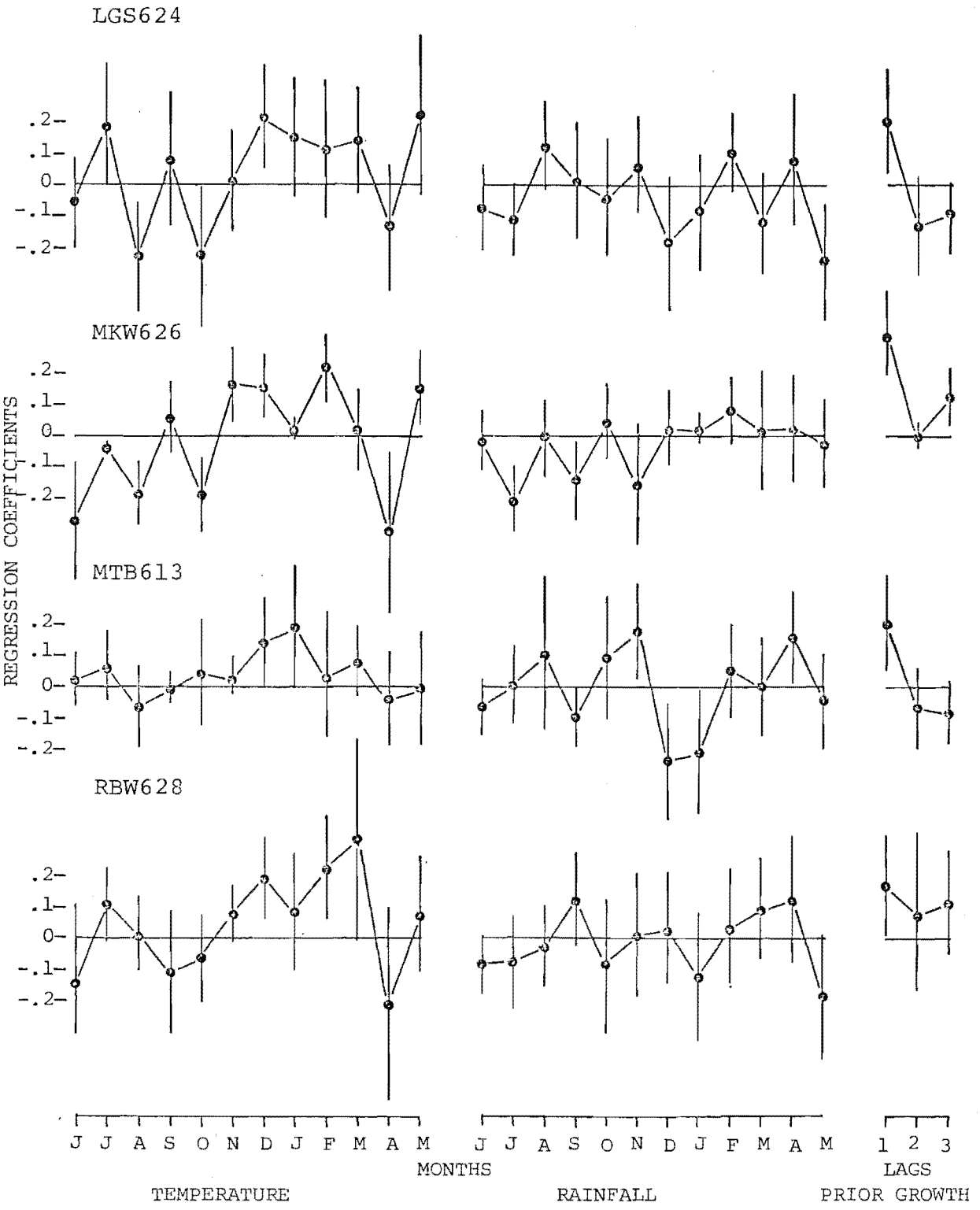


Figure 8.7 continued.

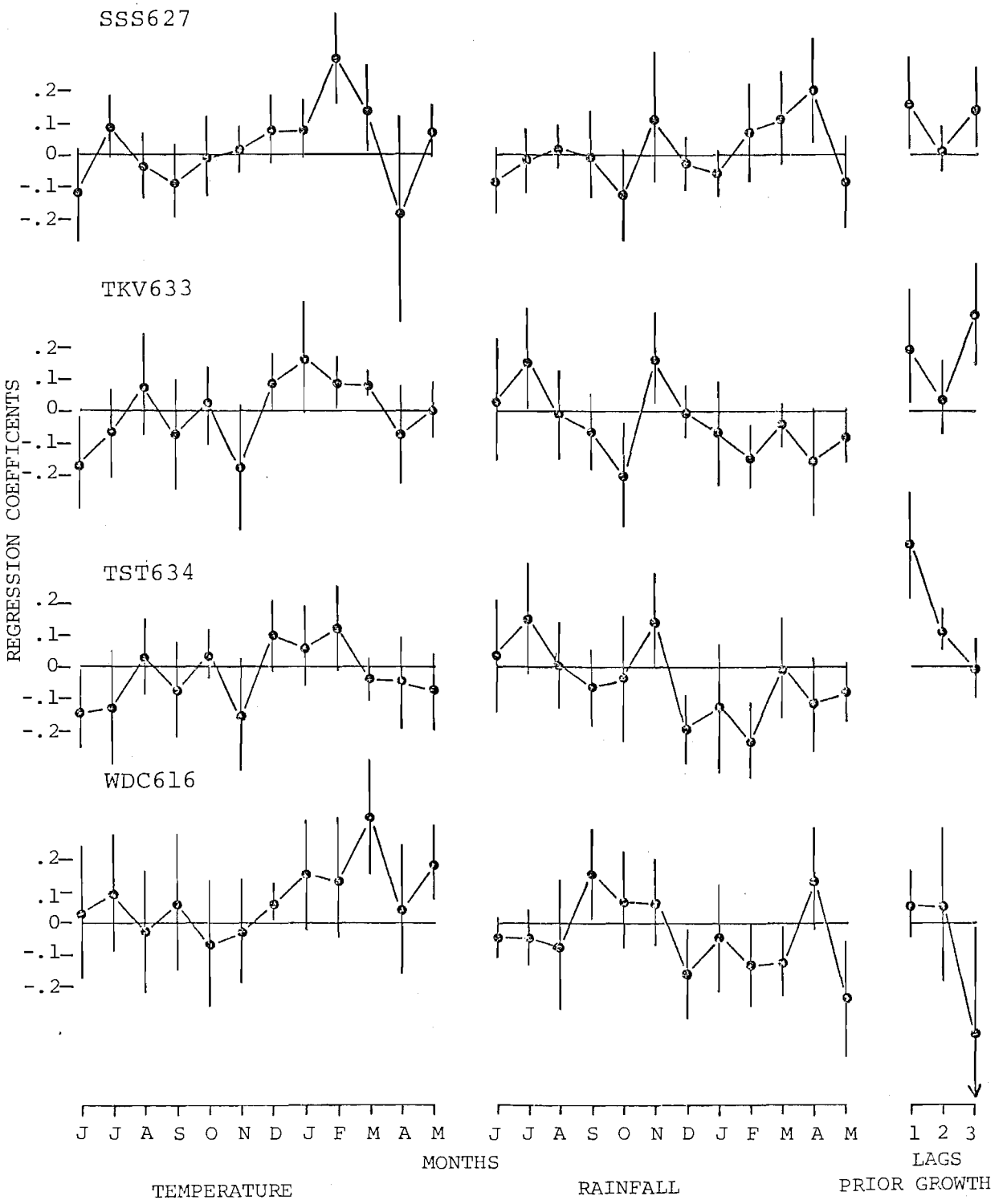


Figure 8.7 continued.

TABLE 8.6 Summarised results for the sixteen timberline *Nothofagus solandri* chronology response functions.

Calibration and verification statistics

	K	r_T^2	r_c^2	r_p^2	r_v^2	RE
AST630	7	0.51	0.34	0.17	0.00	-0.32
CGB625	9	0.40	0.38	0.02	0.05	-0.35
CMP614	8	0.57	0.52	0.05	0.08	-0.49
DBT629	5	0.55	0.55	0.00	0.00	-0.33
ENT615	9	0.56	0.38	0.18	0.21	+0.02
HDC632	7	0.50	0.46	0.04	0.18	-0.30
LCV631	5	0.37	0.28	0.09	0.07	-0.58
LGH618	6	0.57	0.27	0.30	0.02	-0.72
LGS624	7	0.46	0.45	0.01	0.12	-0.14
MKW626	5	0.54	0.36	0.18	0.06	-0.28
MTB613	7	0.44	0.39	0.05	0.14	-0.43
RBW628	7	0.59	0.58	0.01	0.10	-0.18
SSS627	6	0.53	0.47	0.06	0.07	+0.02
TKV633	6	0.46	0.26	0.20	0.12	+0.31
TST634	6	0.44	0.25	0.19	0.26	+0.42
WDC616	7	0.62	0.57	0.05	0.00	-0.65

Distribution of significant regression coefficients

	TEMPERATURE												RAINFALL												PRIOR GROWTH		
	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	1	2	3
AST630					-						+		+					+	-				-		+		
CGB625				+		+					+										+						
CMP614			+				+	+	+	+						+							-			-	
DBT629		+		+			+		+	+		+					-						-				+
ENT615															+				-	-					+		
HDC632				-				+	+	+	+		-					+									-
LCV631			-	+	+				+	+		+			-										+		
LGH618			-	+			+	+	+	+					-			+	-						+		-
LGS624			-		-		+																-		+		
MKW626	-	-	-		-	+	+		+		-	+			-		-								+		+
MTB613																-		+	-	-			+				
RBW628							+		+																+		
SSS627									+	+													+		+		+
TKV633	-						+		+	+							-	+			-				+		+
TST634	-																		-		-				+	+	
WDC616							+			+		+				+			-		-	-		-			-

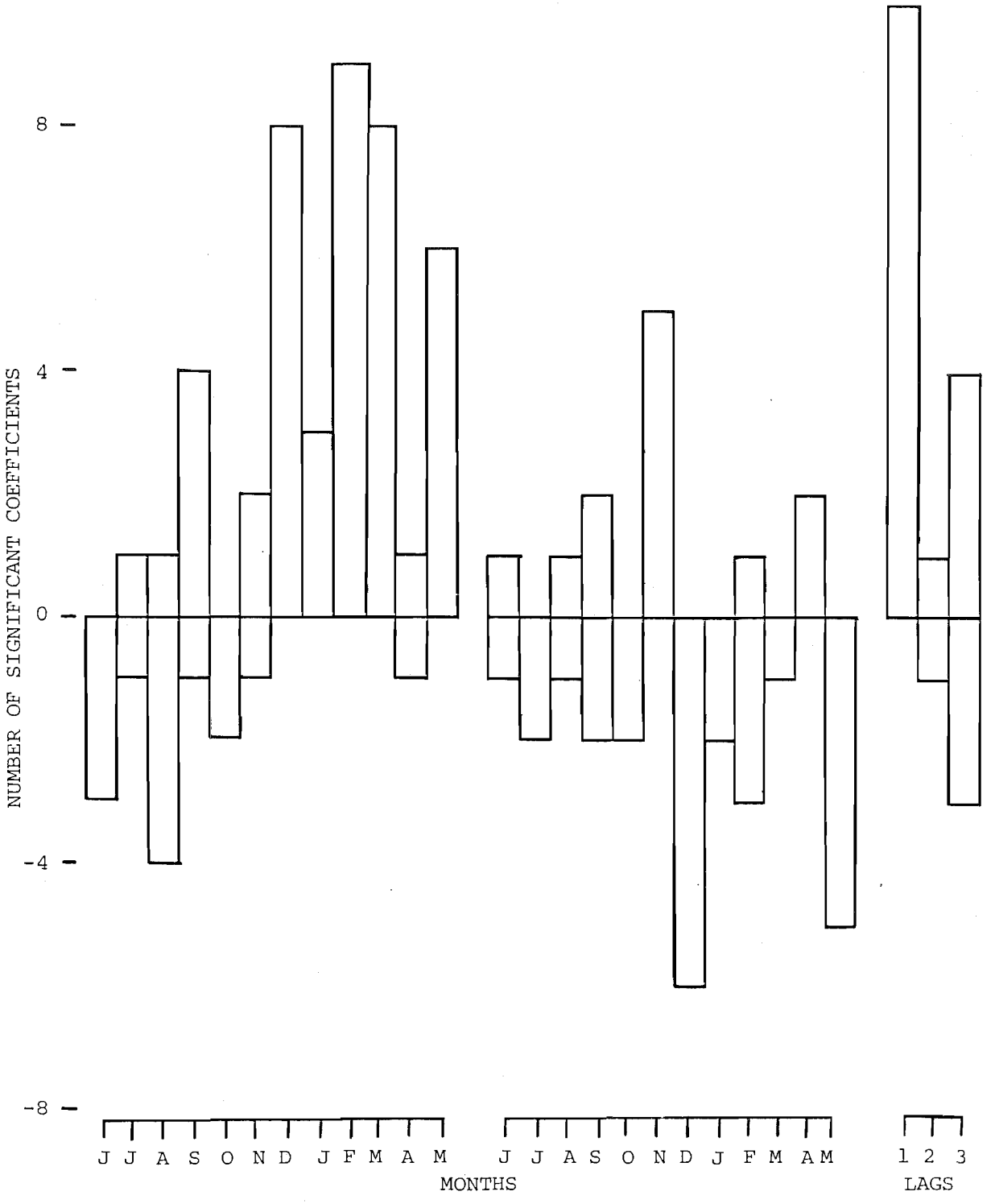


Figure 8.8 Number of significant regression coefficients for each month in the timberline *Nothofagus solandri* response functions.

However, negative associations with June and August temperature could be interpreted in terms of winter damage, particularly by frost and desiccation. Periods of clear fine weather can be associated with severe night frosts and daytime winter desiccation. *Nothofagus solandri* has a freezing resistance to only about $-10^{o}C$ to $-13^{o}C$ (Sakai and Wardle 1978). True frost damage can also result from exceptionally rapid freezing and thawing of foliage (Tranquillini 1979). Rapid heating of frozen leaves when the sun first reaches the site, can cause serious damage. Winter desiccation occurs when soil moisture uptake is inhibited by low soil temperatures and excessive transpiration occurs from the leaves during warm days. This activity results in negative water balances and leaf death (Tranquillini 1979). Winter desiccation damage appears to be common near timberline in the Craigieburn Range (see Appendix 2). Widespread tissue death probably reduces early summer photosynthesis and hence biomass accumulation.

The association between tree growth and spring temperature and rainfall is not strong. Positive associations with temperature in September occur at several sites and could relate to the activation of physiological processes involved in the breaking of bud dormancy by warming temperatures. P. Wardle and Campbell (1976) showed that buds collected from *Nothofagus solandri* seedlings in September, at 1200 m in the Craigieburn Range, broke dormancy significantly earlier than buds collected at the same site in July and August.

The positive association between growth and November rainfall is possibly due to the need for adequate soil moisture for the initiation of shoot expansion and radial growth (see also Section 8.5).

It is during the summer months (December to March) that the most obvious response to climate can be found in the timberline *Nothofagus solandri* chronologies. Almost all of the 16 response functions are positive for all four summer months; 15 in December, 14 in January, 16 in February and 15 in March. The majority of significant temperature response elements occur at this time (Fig. 8.7) and all are positive. 12 of the 13 significant rainfall elements during December to March are negative. The strength of the relationship between tree growth and summer temperature is obvious and these chronologies, along with the timberline *N.menziesii* chronologies, form a very distinct group of tree-ring chronologies.

The reasons for the type of association described above are well documented (e.g. Fritts 1976, Tranquillini 1979). In Chapter 2 it was shown that radial growth in trees from subalpine forests occurred predominantly in January, February and March, while shoot growth occurred in a single flush in December and January. Although growth is initiated earlier (see above) the majority of growth occurs during this short four month period and temperatures at this time are critical. Cool temperatures at either the start or end of this period can shorten the length of the growing season appreciably, while cool temperatures during the growing season can reduce the amount of biomass accumulation. Both result in the formation of a narrower growth ring.

The processes by which temperature limits growth are now discussed briefly. Biomass (carbon) accumulation is dependent on the balance between photosynthesis (carbon assimilation) and respiration (carbon utilization). Photosynthesis is promoted by high light intensities, warm temperatures and abundant soil moisture and is restricted by low air and soil temperatures, drought, high wind speed and short day lengths. Photosynthesis results in the accumulation of carbon in the form of glucose which can be converted to cellulose and deposited in cell walls. Photosynthesis is greatest during the summer months, and in many species, does not occur during winter (Tranquillini 1979). Winter photosynthetic dormancy also appears to occur in *Nothofagus solandri* (Benecke and Havranek 1980b).

Respiration occurs for most of the year. CO_2 fixed during photosynthesis is utilised by transferring the energy stored in the glucose to high energy compounds which are utilised in cell processes. During summer there is usually a net gain in carbon as photosynthesis exceeds respiration, while during winter, as a result of ongoing respiration and effectively zero photosynthesis, there is a net carbon loss. Factors that promote an increase in the length of winter (i.e. shorten the photosynthetically active period) or reduce the rate of photosynthesis during the growing season, result in a reduced annual carbon balance and hence a smaller growth ring is produced.

Associations between tree growth and autumn (April, May) climate occur (Fig. 8.8) but are difficult to explain. In most response functions there tends to be a negative association with May temperature

(6 out of 16 significant) and a negative association with May rainfall (5 out of 16 significant).

8.6.2 Bluff site chronologies

Response functions for the three bluff site *Nothofagus solandri* chronologies are presented in Fig. 8.9. Variance explained by climate ranges from 38% (LKP) to 60% (GHC) and that explained by prior growth from 7% (RTA) to 27% (LKP) (Table 8.7).

The response functions exhibit several similarities, especially a positive association with growing season rainfall (Fig. 8.9 and Table 8.7). Only five temperature coefficients are significant and of these, two are negative. Seven of the nine significant rainfall coefficients are positive and occur from November to April. Regression coefficients for rainfall are largely positive from October to April (Table 8.7) and are positive in all three response functions from November to February. The temperature coefficients are negative in August and from October to January (in all three response functions) but are otherwise largely positive.

The relationships with temperature and rainfall are variable in June, July and August and their interpretation is largely speculative. The positive association with July temperature could be due to the influence of heavy snow falls damaging trees, with a reduced area of photosynthetic tissue present during the subsequent season (see Section 6.7). However, the overall association with climate during the winter months is weak.

The dominating association with climate occurs during the summer months (October to February) when negative temperature elements and positive rainfall elements dominate. This relationship is similar to that obtained by Fritts (1974, 1976) who worked with arid site conifers in western North America. In response functions from western North American arid site tree-ring chronologies and in the three response functions here, the relationship with rainfall is much stronger than with temperature.

It has been suggested that narrow growth rings in western North American tree-ring chronologies may be produced when both food reserves have been limiting and soil moisture depleted (Fritts 1974, 1976).

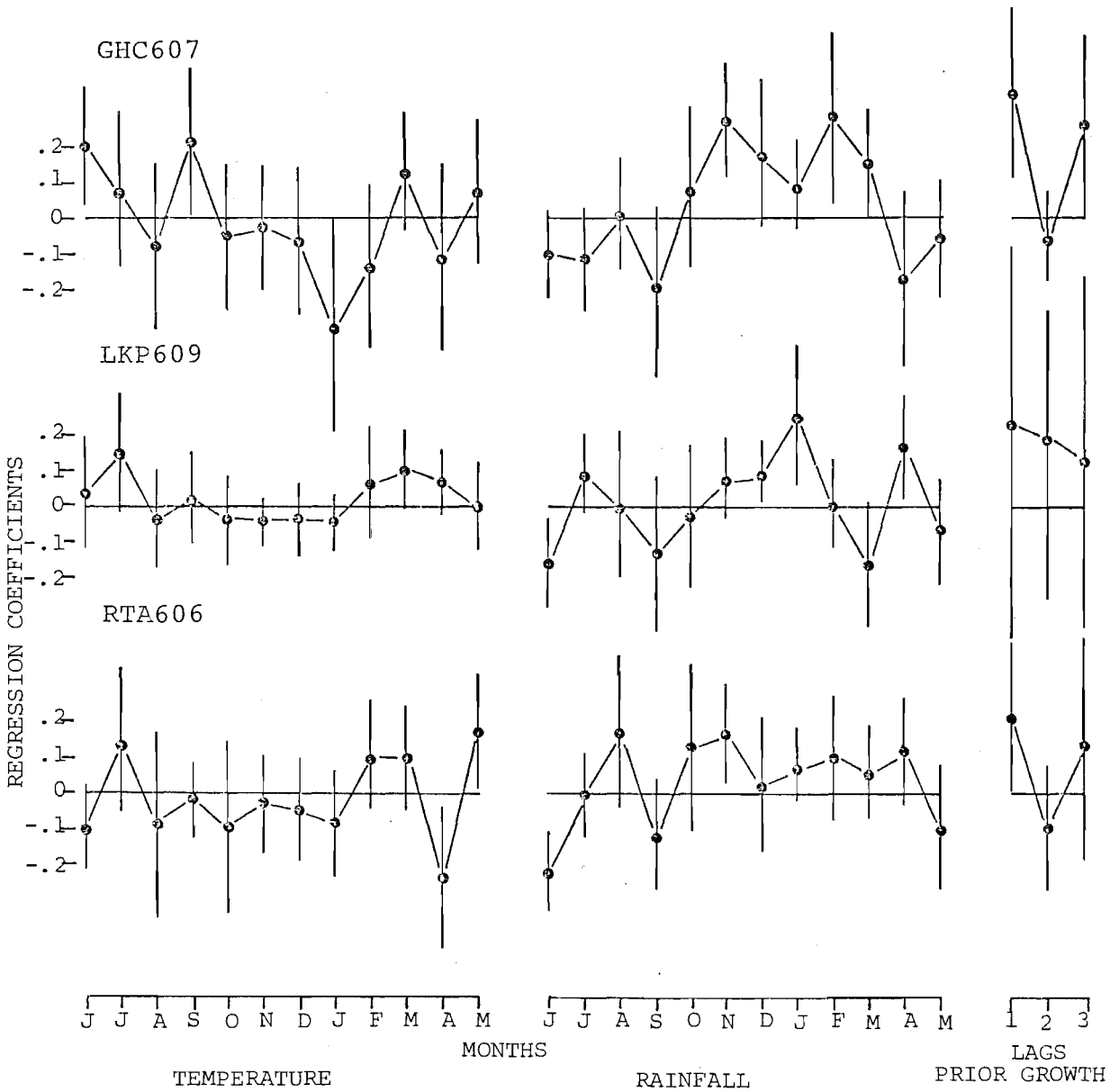


Figure 8.9 *Nothofagus solandri* (bluff site) response functions.

TABLE 8.7 Summarised results for the three bluff site *Nothofagus solandri* chronology response functions.

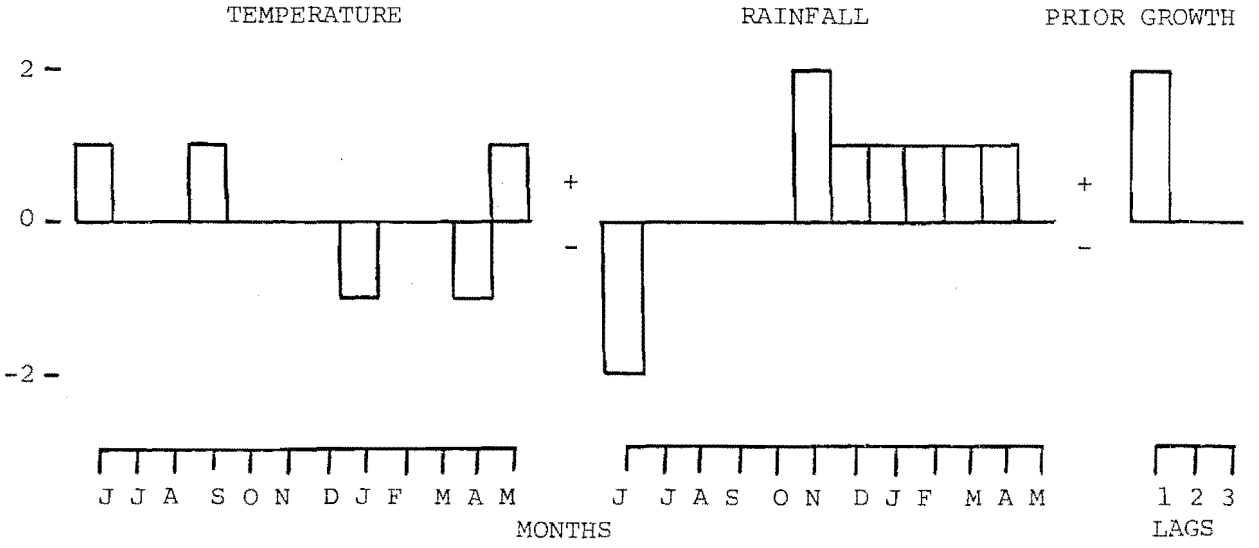
Calibration and verification statistics

	K	r^2_T	r^2_c	r^2_p	r^2_v	RE
GHC607	9	0.76	0.60	0.16	0.18	-0.16
LKP609	9	0.64	0.38	0.27	0.00	-1.06
RTA606	9	0.57	0.50	0.07	0.07	-0.37

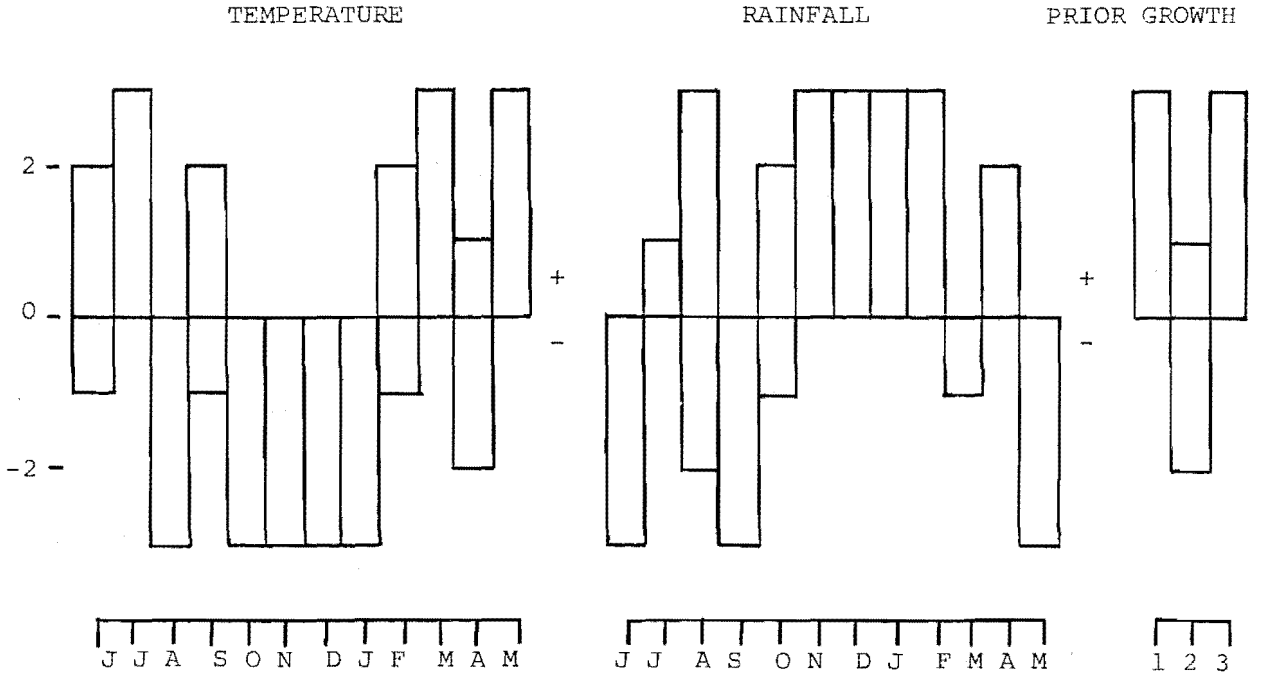
Distribution of significant regression coefficients

	TEMPERATURE												RAINFALL												PRIOR GROWTH		
	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	1	2	3
GHC607	+			+				-										+			+	+			+		
LKP609													-						+	+			+				
RTA606										-	+		-					+							+		

Number of significant coefficients



Number of positive or negative coefficients



Brown (1968, cited in Fritts 1976 p.167) showed that *Pinus ponderosa* in Arizona is able to photosynthesise for much of the winter. Dry periods during the previous autumn, winter and spring result in reduced photosynthesis, with low food reserves for summer growth. Positive regression coefficients for rainfall occurred during these months. However, the response functions presented here lack positive winter and spring rainfall coefficients and it would seem likely that the influence of growing season moisture alone is the main limiting factor to tree growth.

Water deficits can affect growth directly or indirectly. Direct effects occur through desiccation of tissue with damage to the cellular contents. As cells dehydrate, the concentration of ions change , protein structures are altered and the protoplasm contracts and is likely to rupture (Street and Öpik 1976). Indirect effects of water deficits are largely through the influence of plant water shortages on photosynthesis. As water deficits increase, stomatal closure occurs and less CO_2 is absorbed for photosynthesis (Fritts 1976). Stomatal closure also decreases transpiration with increased plant temperature and increased respiration, resulting in reduced carbon accumulation. Water deficits can also affect the biochemical reactions involved in photosynthesis.

The net result of summer water deficits is a reduction in the amount of biomass accumulation and ring width. Almost certainly summer water deficits are the main limit to growth at these bluff sites, but autumn conditions could also have an influence on tree growth. Continued drought into autumn can cause the cessation of growth. The occurrence of positive associations with temperature at this time suggests that cool temperatures also limit growth in some years.

8.7 MISCELLANEOUS CHRONOLOGIES

Of this group of chronologies, three (AHA, MAP, PLC) were developed by LaMarche et al. (1979c) and one (WFT) is from a young stand of *Nothofagus solandri* trees growing at low altitude in the Craigieburn Range. Response functions are presented in Fig. 8.10 and the relevant statistics in Table 8.8.

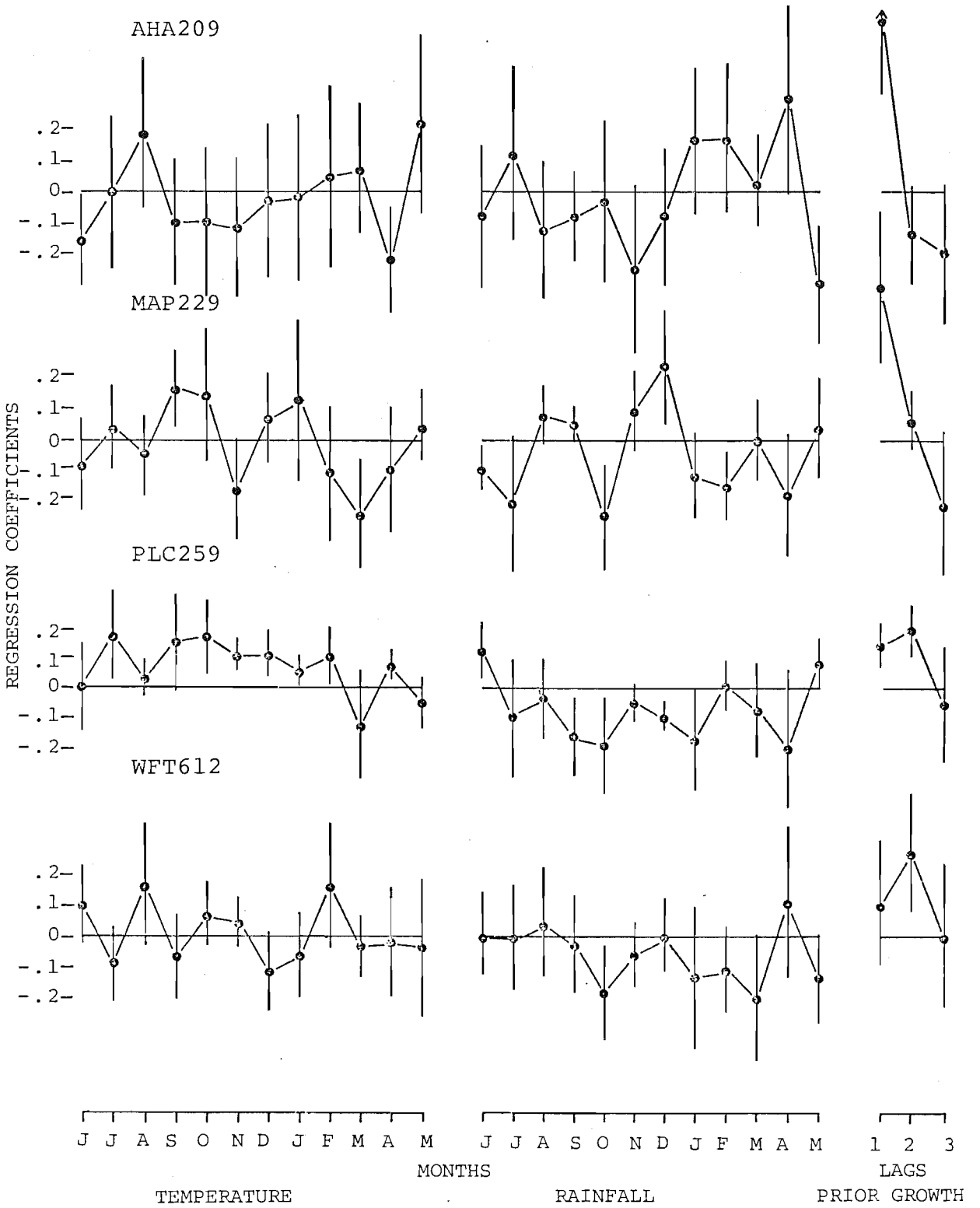


Figure 8.10 Miscellaneous response functions.

TABLE 8.8 Summarised results for the miscellaneous chronology response functions.

Calibration and verification statistics						
	K	r^2_T	r^2_C	r^2_P	r^2_V	RE
AHA209	10	0.52	0.16	0.36	0.05	-0.08
MAP229	7	0.59	0.23	0.36	0.08	-0.07
PLC259	4	0.61	0.52	0.09	0.42	+0.35
WFT612	7	0.31	0.15	0.16	-0.32	-0.36

8.7.1 AHA209 (Grey River Valley, Westland)

Climate accounts for 16% of the variance and prior growth a further 36% of the variance in this *Dacrydium colensoi* chronology. Prior growth is significant at a lag of one year. Few obvious trends are apparent for temperature, with most of the regression coefficients close to zero. Rainfall is negative in spring and early summer and positive from January to April. The negative correlation with rainfall in early summer could be due to frequent cloudy weather with low light intensities delaying the start of growth.

It is likely that both the use of inappropriate climate data and the influence of fire on the stand (see LaMarche et al. 1979c) have contributed towards the weak relationship with climate. A similar weak relationship was obtained between the AHA189 chronology and climate (see Section 8.3.1).

8.7.2 MAP229 (Lake Manapouri, Fiordland)

Climate accounts for 23% of the variance in this *Dacrydium biforme* chronology and prior growth a further 36%. Prior growth at a lag of one year is highly significant. Temperature is directly (positively) related to growth in September (significant) and October, reflecting the need for warm temperatures at the start of the growing season. Rainfall is also significantly negative in October. Rainfall is positive in November and December (significant) but is negative from January onwards. The positive association with November and December rainfall could reflect soil moisture deficits at this time. LaMarche et al. (1979b) note that at this site "soil development is thin on bedrock of granites

and gneisses". Disturbance from road construction has occurred at this site (LaMarche et al. 1979c) and the poor association with climate could be, in part, due to this.

8.7.3 PLC259 (Arthurs Pass, Westland)

A very strong response to climate is present in this *Phyllocladus alpinus* chronology. 52% of the variance is explained by climate and only 9% by prior growth. The response function (Fig. 8.10) has a strong positive association with temperature and negative association with rainfall. Temperature coefficients are positive from June to February and again in April and are significantly positive in July, September to February and April. Rainfall coefficients are negative in all months except June, February and May and are significantly negative in September, October, December and January. Significant positive rainfall coefficients occur in June and May. This direct relationship with summer temperature occurs because low temperatures limit photosynthesis and other physiological processes necessary for rapid growth. The negative response with rainfall presumably reflects periods of fine weather with warm temperatures when rainfall is low. This response function indicates that at subalpine sites this species has a strong growth-climate relationship. If further *P.alpinus* chronologies are developed it may be possible to use them for palaeoclimatic reconstructions.

8.7.4 WFT612 (Cass Basin, Canterbury)

This chronology was developed from a stand of young *Nothofagus solandri* trees growing at low altitude on the floor of Cass Basin, adjacent to the Craigieburn Range. Growth rates were fast (mean ring width of 3.45 mm) and crossdating was poor. The low amount of variance explained by climate is therefore not surprising. Most of the variance in this chronology is probably due to individual tree "noise". Few trends are apparent in the response function, although rainfall is negatively associated with growth during the growing season. The relevance of this is not clear, although it could be that cloudy wet weather correlates with reduced photosynthesis and hence reduced radial growth.

8.8 DISCUSSION

8.8.1 Verification

In interpreting response functions it is important to consider the short length of the analysis period (48 years). The relationship between tree growth and climate is established for this period and assumed to hold true for longer periods. Verification is a check on the time stability of the relationship calculated between tree growth and climate for the calibration period. However, most of the verifications calculated here are not significant (see Tables 8.1 to 8.8). It is probable that this is in part due to the short time period used (16 and 25 years). Of the verifications undertaken for the 25 year time period, 50% have positive RE values, while for the 16 year period only 25% have positive RE values.

The reliability of the response functions developed can be assessed by comparing the response functions in the different chronology groups. They are very similar except for the *Libocedrus bidwillii* chronology group and can also be interpreted in terms of our understanding of the biology of the species. The successful calibration and verification of the temperature reconstruction over a 120 year period (Chapter 9) is further evidence of time stability in the trees' response to climate. As the response functions are not used directly to reconstruct climate, but rather to identify climatic factors limiting growth, time stability is less of a problem here than it is in reconstruction (Chapter 9).

8.8.2 Response function quality

Assessment of the usefulness of tree-ring chronologies and their response functions for climatic reconstructions is not easy. Pittock (1982) has suggested that trees which respond well to climate will have considerable common variance (%Y). Comparison of variance explained by climate in the response function and common variance in the ANOVA helps interpret the usefulness of chronologies for climate reconstruction. The reliablity of this approach has been questioned by Cropper (1982c), who has pointed out problems associated with variable sample sizes. Cropper suggests that use of the signal-to-noise ratio (S/N) (Section 4.3.5) enables sample size to be taken into account. Percentage common signal in the final chronology can then be calculated as,

$$\% \text{ common signal} = \frac{100(S/N)}{(S/N+1)}$$

This can be plotted against variance in the chronology explained by climate (Fig. 8.11) and used to assess the quality of the calibration against climate in the response function.

The resultant plot (Fig. 8.11) can be divided into four quadrants which can be interpreted as follows (Cropper 1982c),

Quadrant A: These chronologies have less calibrated variance than "noise".

Quadrant B: Again climatic calibration is predominantly against chronology "noise".

Quadrant C: Climate data has calibrated a mixture of signal and "noise".

Quadrant D: Calibration is predominantly against signal and little "noise" occurs.

The closer a chronology is plotted to the top right-hand corner (E), the better the chronology quality and its climate calibration. Chronologies that fall into quadrants C and D offer greater potential for reconstruction than those from quadrants A and B.

The chronologies developed here fall in quadrants A and D. All the *Nothofagus solandri* chronologies and all but one of the *N.menziesii* chronologies occur in Quadrant D. However, three of the six *Libocedrus bidwillii* chronologies are in Quadrant A. Selection of more appropriate climatic variables for the response function analysis may improve the position of the *L.bidwillii* chronologies.

8.8.3 General discussion and conclusions

The discussion of the response function for the RANDOM chronology (Section 8.2) highlights important limitations of the response function technique. The need for extreme caution in interpreting single response functions is evident. Even the occurrence of trends in the regression coefficients need careful interpretation. A knowledge of the biology of each species is essential for interpreting response functions but the most reliable aid to interpretation is to obtain good replication from other tree-ring chronologies. The results presented for the timberline *Nothofagus solandri* and *N.menziesii* chronologies are examples of good replication. The poor replication between the *Libocedrus bidwillii* chronologies indicates that possibly poorly selected climate records were used and also that there are considerable ecological differences between the different sampled stands.

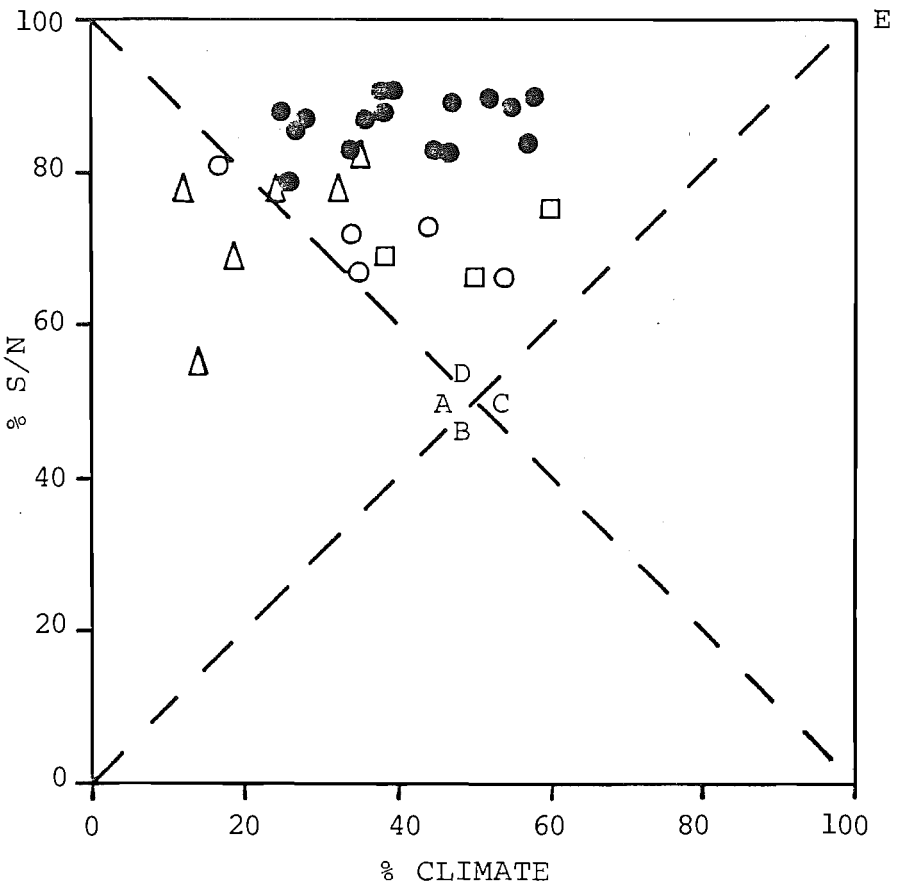


Figure 8.11 Common signal in final chronology (%S/N) plotted against the variance in the final chronology explained by climate (% CLIMATE). ● *Nothofagus solandri* (timberline), O *N.menziesii*, □ *N.solandri* (bluff sites) and Δ *Libocedrus bidwillii*.

The sequence of response functions described for the *Nothofagus solandri* altitudinal transect shows a clear pattern with changing altitude which largely supports the observations made in Section 5.4. With increasing altitude the overriding influence of temperature on tree growth becomes apparent. At lower altitudes a variety of factors can influence tree growth. Trees sampled close to the timberline ecotone are likely to have a strong and clear temperature signal, while the influence of climate at lower altitudes is less clear.

The timberline group of chronologies analysed here *(Nothofagus menziesii* and *N.solandri)* have response functions similar to those of other species developed from trees near upper altitudinal or latitudinal limits. *Pinus longaeva* trees near timberline in the White Mountains of California are positively correlated with previous autumn and current summer temperature (LaMarche and Stockton 1974). A strong positive relationship has been observed between *Picea abies, Pinus cembra* and *Larix decidua* trees and summer temperature in the Swiss Alps (Schweingruber et al. 1978). In Tasmania, chronologies developed from subalpine forest trees of two *Arthrotaxis* species are positively related to temperature during an 18 month period up to and including the growing season (LaMarche and Pittock 1982). Similar positive responses to temperature also occur in Arctic trees (e.g. Garfinkel and Brubaker 1980, Kuivinen and Lawson 1982). The reasons for these responses to temperature have already been discussed and are common to all the examples given. As several of these temperature sensitive chronologies have been successfully used for reconstructing past temperatures (e.g. LaMarche 1974a, Jacoby and Cook 1981, LaMarche and Pittock 1982) it is considered that much potential exists for the reconstruction of past temperatures in New Zealand using the grid of timberline *Nothofagus* chronologies presented here.

The response functions developed here for the three bluff site *Nothofagus solandri* chronologies are similar to those developed from drought sensitive trees elsewhere (e.g. from western North America, Fritts 1976). Chronologies developed from *Quercus* species in England are positively related to growing season rainfall and negatively related to rainfall during the previous growing season (Pilcher and Gray 1982, Pilcher and Hughes 1982). Positive responses to growing season rainfall have also been found for tree-ring chronologies in Tasmania (Campbell 1982), South America (Holmes et al. 1979) and

eastern North America (Cook and Jacoby 1977) and these, along with those from England (e.g. Briffa et al. 1983) and western North America (Fritts 1976) have been successfully used to reconstruct past rainfall. The potential exists for using the three bluff site *N.solandri* chronologies for similar reconstructions.

CHAPTER NINE

TRANSFER FUNCTION ANALYSIS

9.1 INTRODUCTION

Reconstructions of past temperature, rainfall and riverflow for various stations in New Zealand are presented in this chapter. These are the first calibrated and verified annual reconstructions of New Zealand climate and riverflow prior to instrumental records. The techniques used to obtain these reconstructions have been described in Chapter 7 and are applied to tree-ring chronology grids in this chapter. A grid of several tree-ring chronologies is used to predict climate using principal component multiple regression techniques. The relationship developed is then verified against independent climate data and the cases with the best calibration and verification statistics are used to reconstruct climate and riverflow prior to instrumental records.

As a large number of tree-ring chronologies have been developed, it is necessary to select the most suitable chronologies for reconstructing climate and riverflow. This is undertaken in the first part of this chapter (Sections 9.2 - 9.4); four reconstructions are developed. These are discussed in Section 9.5.

9.2 TEMPERATURE RECONSTRUCTIONS

9.2.1 Introduction

The steps involved in choosing a particular combination of tree-ring chronologies for reconstructing past New Zealand temperature are described in this section and a reconstruction presented. This essentially involves establishing the particular combination of tree-ring chronologies that has the best calibration and verification statistics when regressed against modern temperature. Several preliminary analyses identified the chronologies which are most suitable for past temperature reconstruction. Initial chronology selection was based on several criteria; that the chronology was at least 250 years long, that it had a large amount of common variance in the ANOVA (Chapter 6), that it had a strong temperature signal in its response function (Chapter 8), and that it contributed towards a good spatial spread of chronologies. Six *Nothofagus solandri*

chronologies (Canterbury and Fiordland) and five *N.menziesii* chronologies (South Westland and Fiordland) were chosen (Table 9.1). Although not correlating strongly with temperature *Libocedrus bidwillii* chronologies were also used initially because of their better spatial distribution over the South Island and to compare with the *Nothofagus* chronologies.

A summer temperature series, derived from the New Zealand temperature series (see Chapter 7, Salinger 1980a) was used because of the strong positive association between many of the tree-ring chronologies and growing season temperature. The summer temperature series consisted of the mean December to March temperature. December to March are New Zealand's warmest months and are the time when most *Nothofagus solandri* growth takes place (Chapter 2). The year assigned to each summer temperature mean was taken as the year in which December fell, so as to coincide with the tree-ring year (see Section 4.2.3). As the available temperature record is long, it was divided into two 61 year periods; 1853-1913, 1914-1974. This allowed sub-sample replication (Chapter 7) with the tree-ring data being calibrated and verified against both periods.

Three groups of analyses (runs) were undertaken before the final combination of tree-ring chronologies was chosen for reconstructing past temperature. In the first run, the use of growth from years t, t-1 and t+1 was evaluated for each species group separately. In Run 2, different combinations of tree-ring chronologies from within each species group first, and then using the three species together, were regressed against climate. In Run 3, the number of chronologies used was reduced further and a chronology combination that both calibrates and verifies significantly was chosen for reconstructing past temperatures.

9.2.2 Calibration and verification, Run 1

In Run 1, the three species groups were regressed against temperature separately. The inclusion of growth lagged a year ahead (t+1) and a year behind (t-1) was varied. The calibration results are tabulated in Table 9.2. Variance explained in the regressions ranges from 9% to 52%. The results were not verified as this was only a preliminary run. An increase in the amount of explained variance occurs when growth from years t-1 and t+1 is included with current year's growth (t). This increase could result from the concurrent increase in the number of predictors (K) entering the regression

TABLE 9.1 Characteristics of the tree-ring chronologies used for reconstructing New Zealand summer temperature.

Chronology	Species[1]	Date[2]	%Y[3]	% climate[4]
AHA189	LB	1525	28	12
ARM189	LB	1450	18	19
CGB625	NS	1740	44	38
CRC601	LB	1460	27	25
CRG189	LB	1492	34	35
HDC632	NS	1730	39	46
KEA637	NM	1580	28	54
LCV631	NS	1730	45	28
LGH618	NS	1740	41	27
LKE636	NM	1676	31	44
MKW626	NS	1730	36	36
OBL610	NM	1584	34	34
OKA189	LB	1732	24	33
TKV633	NS	1630	38	26
TRK602	LB	1526	17	14
UHV635	NM	1710	38	17
UTV611	NM	1622	25	35

Notes:
1. LB - *Libocedrus bidwillii*, NM - *Nothofagus menziesii*, NS - *N.solandri*
2. Starting date of chronology
3. Common variance in the ANOVA (Chapter 6)
4. Variance explained by climate in the response function analysis (Chapter 8)

TABLE 9.2 Run 1, New Zealand summer temperature reconstructions. Initial calibration of New Zealand summer temperature for two time periods using tree-ring chronologies from the three species separately. The inclusion of growth in years *t*-1 and *t*+1 is varied.

Calibration period:	1853-1913			1914-1974		
	K_o[1]	K[2]	r^2[3]	K_o	K	r^2
Nothofagus solandri (n=6 chronologies)						
t, *t*-1	12	4	37	12	4	10[NS4]
t, *t*+1	12	4	40	12	4	52
t, *t*-1, *t*+1	18	4	50	18	5	52
Nothofagus menziesii (n=5 chronologies)						
t, *t*-1	10	2	29	10	3	24
t, *t*+1	10	2	33	10	3	32
t, *t*-1, *t*+1	15	2	32	15	4	33
Libocedrus bidwillii (n=6 chronologies)						
t, *t*-1	12	4	18[NS]	12	2	9[NS]
t, *t*+1	12	3	26	12	4	36
t, *t*-1, *t*+1	18	6	34	18	5	37

Notes:
1. K_o - total number of predictors (i.e. number of chronologies used).
2. K - number of predictors (principal components) entering the regression. Each principal component includes some information on all the original (K_o) predictors
3. r^2 - variance reduced (%)
4. NS - not significant at the 99.9% level (n-1-k d.f.)

but the results presented in Table 9.2 indicate that this is not the case. For example, four predictors entered the regression in the 1853-1913 period for the three *Nothofagus solandri* regressions, yet the total number of predictors (K_o) increases from 12 to 18, and variance explained increases from 37% to 50%.

Run 1 results indicate that the *Nothofagus solandri* chronology grid explains much of the variance (up to 52%) in the summer temperature series. Explained variance is lower (up to 37%) with the other two species. Explained variance is greatest in the case with *t*, *t*-1, *t*+1, although it is also high for *t*, *t*+1. Because of computing expenditure limits, it was not possible to undertake further reconstructions with both options (i.e. *t*, *t*-1, *t*+1 and *t*, *t*+1). In subsequent reconstructions (for temperature, rainfall and riverflow) grids including growth in years *t*, *t*-1, *t*+1 for each chronology, were used.

9.2.3 Calibration and verification, Run 2

In Run 2, various combinations of chronologies were regressed against summer temperature. Calibration and verification results are tabulated in Table 9.3. The first three cases are taken from Run 1 and verification results are included. Although some of these verifications are significant (at the 99.9% level) and RE values positive, explained variance in verification is not great. The two *Nothofagus* groups provide better estimates of summer temperature than the *Libocedrus bidwillii* group. Case 4 is for the combined *Nothofagus* species group with a grid of 11 chronologies (giving 33 predictor variables). Explained variance in both the calibrations and verifications is higher than for the two *Nothofagus* species individually. However, one of the RE values is negative. The increase in explained variance is probably in part due to a greater number of predictors (K) entering the regression (especially for the 1914-1974 period). The decreased percentage of explained variance in verification indicates some "artificial predictability" in the calibration regression.

Cases 5 and 6 (Table 9.3) are mixed species grids incorporating chronologies from all three species. Chronologies used were chosen to give a widespread distribution of chronologies. However, the results do not show noticeable improvements in explained variance; in one case verification is not significant and the RE value negative. In both cases, the two time periods show considerable differences in explained variance, especially during verification.

TABLE 9.3 Run 2, New Zealand summer temperature reconstructions. Calibration of New Zealand summer temperature using several combinations of tree-ring chronologies. All combinations include growth in years t, t-1 and t+1.

Calibration period:	1853-1913				1914-1974			
	K[1]	r_c^2[2]	r_v^2[3]	RE[4]	K	r_c^2	r_v^2	RE
Case 1	6	34	4[NS 5]	-0.47	5	37	0[NS]	-0.28
2	2	32	25	0.00	4	33	30	-0.04
3	4	50	23	0.07	5	52	14[NS]	0.01
4	5	52	41	0.17	8	63	31	-0.03
5	6	63	41	0.12	9	61	29	0.09
6	8	54	18[NS]	-0.20	6	39	36	0.21

Chronologies used:

Case 1. CRC, TRK, AHA, ARM, CRG, OKA (K_o[6] = 18)

2. LKE, KEA, OBL, UHV, UTV (K_o = 15)

3. CGB, HDC, LCV, LGH, MKW, TKV (K_o = 18)

4. Cases 2 and 3 above (K_o = 33)

5. OBL, TKV, LKE, UHV, KEA, CRC, MKW, HDC (K_o = 24)

6. CRC, TRK, OBL, KEA, UTV, TKV (K_o = 18)

Notes:
1. K - number of predictors entering regression
2. r_c^2 - variance reduced in calibration (%)
3. r_v^2 - variance reduced in verification (%)
4. RE - reduction of error statistic
5. NS - not significant at the 99.9% level (n-1-k d.f.)
6. K_o - total number of predictors

Run 2 shows that improved calibrations and verifications can be obtained by combining chronologies from the two *Nothofagus* species. However, the inclusion of *Libocedrus bidwillii* chronologies does not markedly improve the results. This is due to the poor response of this species to temperature (see Section 8.2), which probably reflects a biological difference in response to temperature. The considerable variation between calibration and verification results for the two time periods suggests that further chronology selection is needed.

9.2.4 Calibration and verification, Run 3

In the final run (Table 9.4), the number of chronologies used was reduced and different combinations of these tested. The *Libocedrus bidwillii* chronologies were excluded (see above) and a subset of the original *Nothofagus* chronologies used. Selection of *Nothofagus* chronologies was based in part on the regression weightings placed on the individual chronologies in the calibrations already undertaken. The resulting chronology grid represents a good spatial spread of South Island *Nothofagus* chronologies, with sites from the Craigieburn Range (three), Landsborough Valley (one), Hollyford Valley (one) and Murchison Mountains (four). The different combinations used maintains the spatial spread of chronologies but varies the actual chronologies used from the Craigieburn Range and the Murchison Mountains. The total amount of variance explained in the calibrations is not as high as in Cases 4 and 5 but verification values are on average greater than for the earlier cases. RE values are all positive. Of most importance is the much greater degree of consistency in the statistics between the two time periods and between verification and calibration. Case 10 includes all nine chronologies and gives the worst overall result, while Case 9 with only seven chronologies gives the best overall result and is used to reconstruct New Zealand summer temperature.

9.2.5 Temperature reconstruction

The location of the chronologies used in Case 9 are marked on Fig. 9.1. The two Craigieburn Range chronology sites (HDC, MKW) are approximately 14 km apart. In the Murchison Mountains, the two Takahe Valley chronology sites (OBL, TKV) are approximately 15 km from the LKE chronology site. The OBL and TKV chronologies were developed from *Nothofagus menziesii* and *N.solandri* trees in the same valley. Although the sites used in this reconstruction do not form an even, high density grid (Kutzbach and Guetter 1980), they were developed from temperature

TABLE 9.4 Run 3, New Zealand summer temperature reconstructions. Calibration of New Zealand summer temperature using combinations of *Nothofagus* tree-ring chronologies. All combinations include growth in years t, t-1 and t+1.

Calibration period:	1853-1913				1914-1974			
	K	r_c^2	r_v^2	RE	K	r_c^2	r_v^2	RE
Case 7	5	47	38	0.13	8	61	37	0.14
8	6	54	45	0.14	5	59	46	0.22
9*	7	59	49	0.22	6	58	46	0.19
10	6	51	44	0.16	5	60	26	0.09

Chronologies used:

Case 7. LKE, KEA, OBL, UTV, UHV, CGB, HDC, TKV (K_o = 24)

8. LKE, KEA, OBL, MKW, UHV, CGB, HDC, TKV (K_o = 24)

9* LKE, KEA, OBL, UHV, HDC, MKW, TKV (K_o = 21)

10 LKE, KEA, OBL, UTV, UHV, CGB, HDC, MKW, TKV (K_o = 27)

Notes: as in Table 9.3

* Case 9 is used in the final summer temperature reconstruction

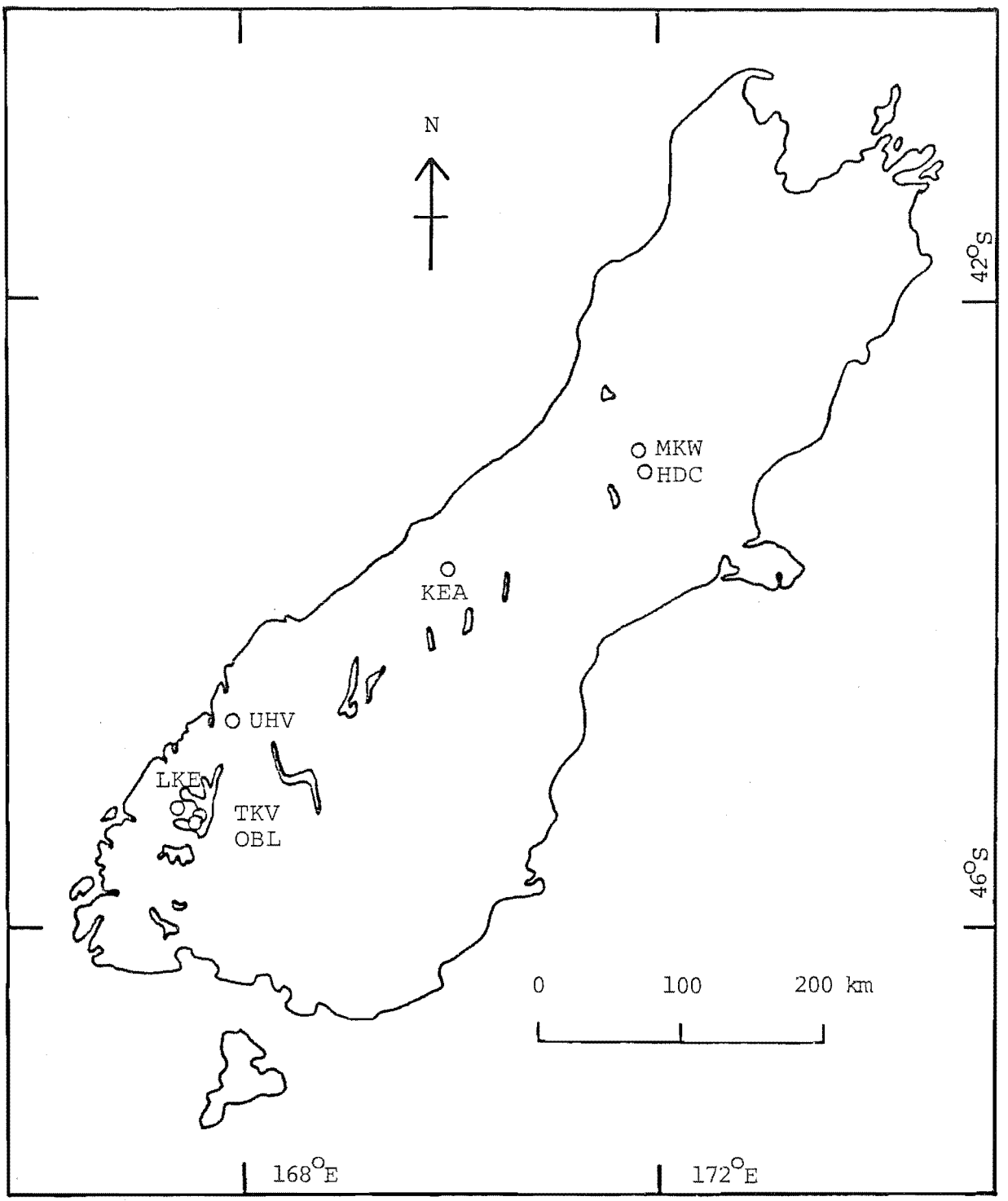


Figure 9.1 Location of timberline *Nothofagus solandri* (MKW, HTB and TKV)and timberline *Nothofagus menziesii* (KEA, UHV, LKE, OBL) chronologies used to reconstruct New Zealand summer temperature.

sensitive trees growing close to the alpine timberline and located along a 400 km section of the main axial ranges of the South Island (700 km long). This spread of tree-ring chronologies takes advantage of the slightly different climatic responses of the individual chronologies and improves the ability to reconstruct regional temperature patterns.

Case 9 performs well in subsample replication, explaining 59% of the variance in the 1853-1913 calibration period and 58% of the variance in the 1914-1974 calibration period. Verification of these two regression equations is also significant (at the 99.9% level) with 49% and 46% variance explained respectively (Table 9.4). RE values are positive in both cases. The regression for the 1853-1913 period calibrates and verifies better than for the 1914-1974 period. These promising verification results show that there is considerable reliability in the calibration relationship.

The observed and estimated value of New Zealand summer temperature developed using the chronology grid from Case 9 for the calibration period 1853-1913 and verification period 1914-1974 are plotted in the upper part of Fig. 9.2. In general, the reconstructed values have a smaller amplitude than the observed values, a feature also noted in other reconstructions (e.g. Pilcher and Hughes 1982). Both annual values and longer term variations are portrayed. The major discrepancy between the two series occurs in the 1950's. A well documented temperature increase began in the 1950's in New Zealand (Salinger 1982a) and is apparent in the observed summer temperature series (Fig. 9.2). The reconstruction of temperature appears to lag behind this increase; an estimated temperature increase is not shown until the 1960's (see Section 9.5.1). However, similar lags are not apparent at other times when temperature changes have occurred (e.g. temperature decrease for 1880 to 1920). Excepting this discrepancy, the reconstruction of summer temperature portrays both annual variations and longer term trends in the observed series. The regression equation developed here for the calibration period gives a verifiable approximation of New Zealand summer temperature.

The regression equation was then applied to the same tree-ring chronology grid for the period 1730-1852 and a reconstruction of summer temperature developed. This reconstruction is presented in the lower part of Fig. 9.2. The reconstructed mean summer temperature values

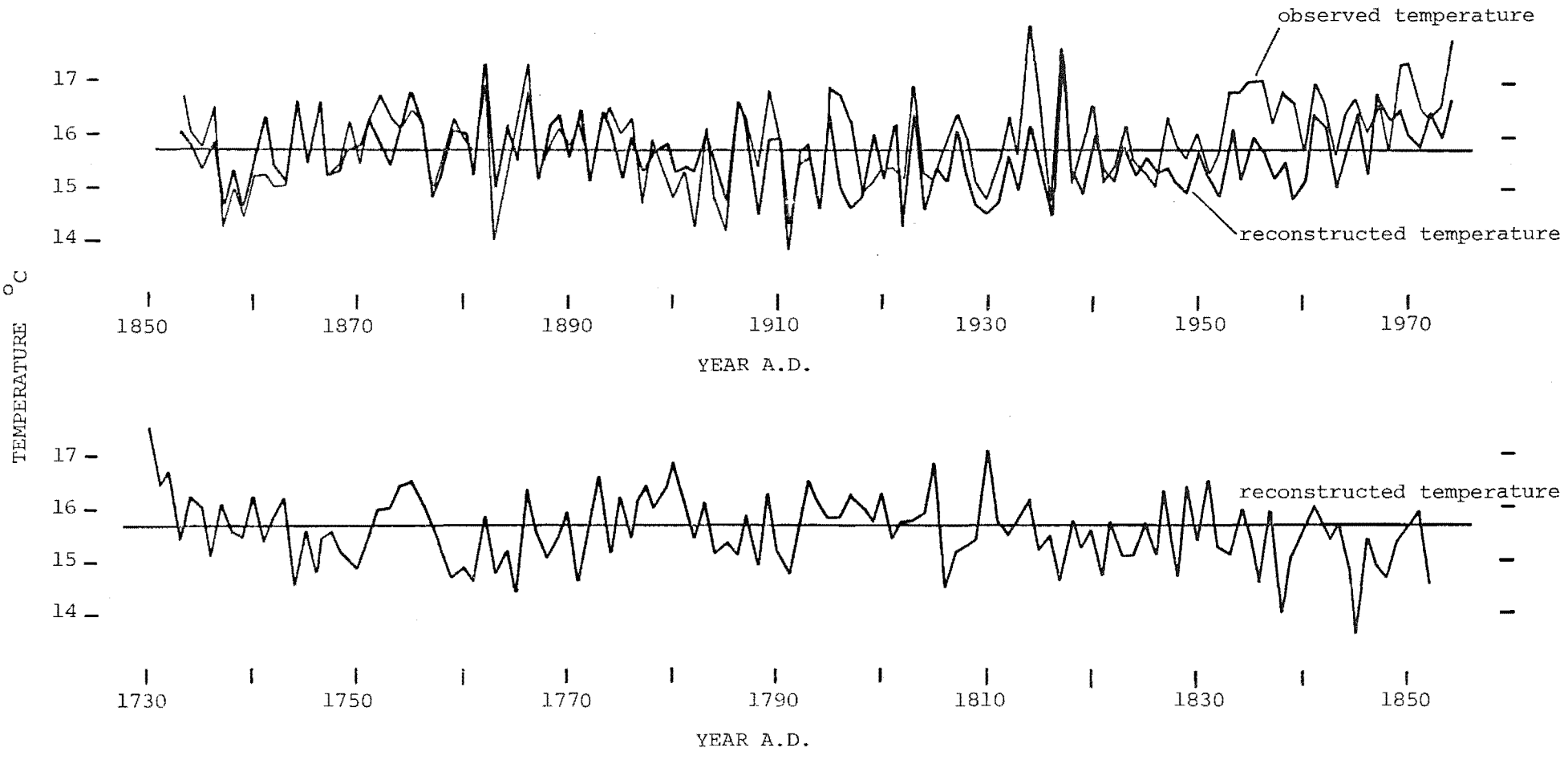


Figure 9.2 Reconstruction of New Zealand summer temperature from 1730 to 1974 A.D.

for the complete 1730-1974 period are listed in Appendix 7. Because two of the chronologies used to develop this temperature reconstruction do not extend prior to 1730, the reconstruction only extends back this far.

9.3 RAINFALL RECONSTRUCTIONS

9.3.1 Introduction

In this section, the steps involved in developing rainfall reconstructions are described. The three low altitude *Nothofagus solandri* chronologies (GHC, LKP, RTA) are strongly associated with growing season rainfall and were used here. To improve the grid size, four chronologies from the Craigieburn Range (LGH619, LGH622, DBT, SSS) were also used. These extra chronologies all show a positive association with some component of growing season rainfall, although only the two LGH chronologies have significant coefficients (Chapter 8).

Response function analysis (Chapter 8) shows November, December and January rainfall to be strongly associated with growth in all three of the bluff site chronologies and to a lesser extent with the other four chronologies. For this reason, reconstructions of total rainfall were undertaken for this period. Choice in the selection of suitable rainfall records was constrained by two factors; record length and quality, and proximity to tree-ring chronology sites. Five rainfall records were chosen; Highfield, Amberley, Lake Coleridge, Ashburton and Orari Gorge (Fig. 9.3). No long reliable rainfall records are available from the Castle Hill and Flock Hill Basins. Lake Coleridge is located within the foothills but further south. The other climate stations are located on the Canterbury Plains and were included because of the importance of rainfall to agriculture in this area. Water deficients are a major feature of the climate of the Canterbury Plains. Deficients occurring for three consecutive months or longer occur in 50% of years in Canterbury and are greatest in December and January (Coulter 1966). The long Lincoln College rainfall record was not used because of inhomogeneities in this record (Salinger 1981).

9.3.2 Calibration and verification, Run 1

As record lengths are short, calibrations are only for a 50 year period, ending in either 1974 or 1978, depending on the record. Initially all five rainfall records were calibrated against the tree-ring grid (21 predictors including growth in years t, t-1 and t+1 for

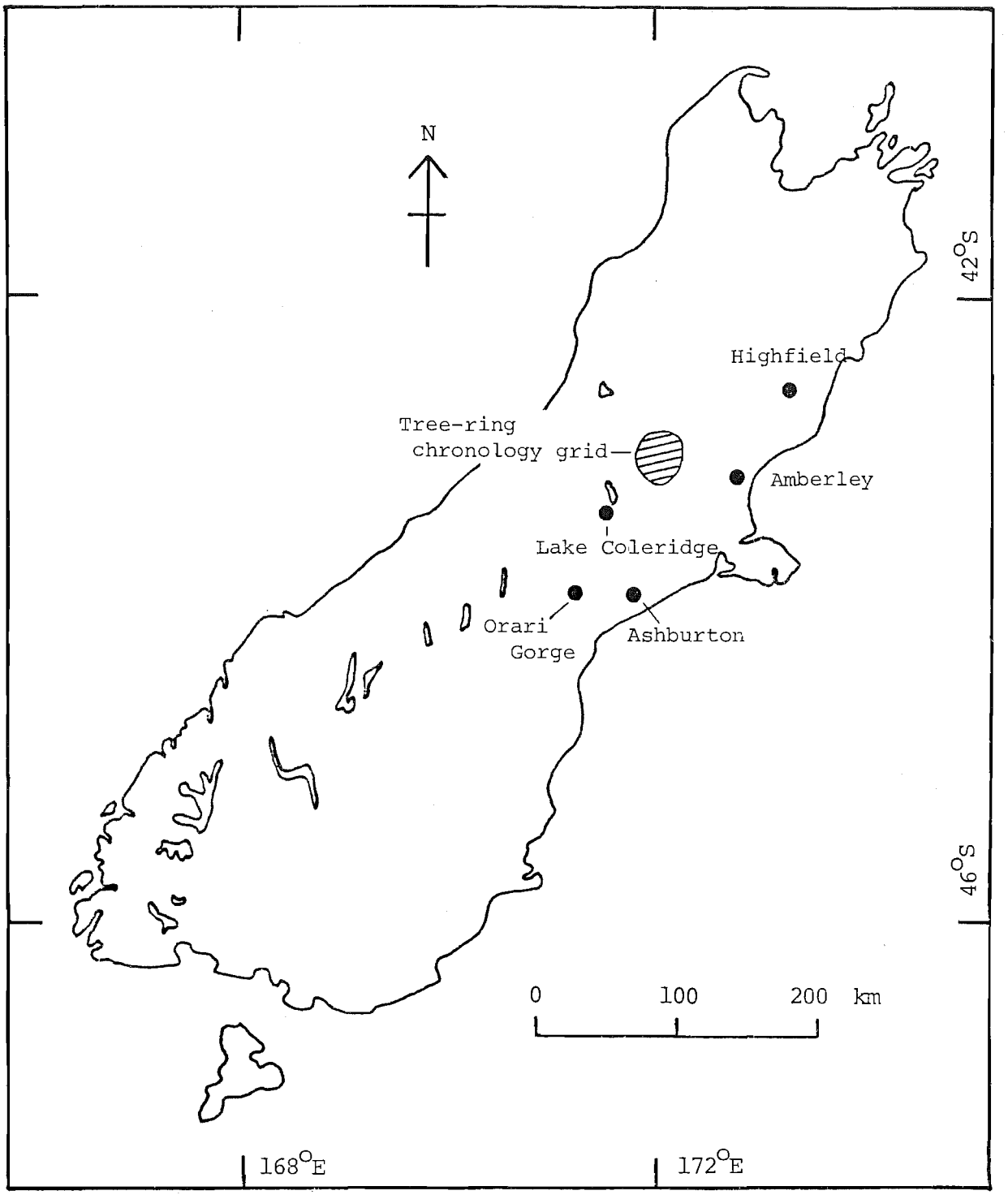


Figure 9.3 Location of the rainfall sensitive tree-ring chronology grid and stations for which rainfall is reconstructed.

seven chronologies) and two subsamples of the grid. The first subsample included the three bluff site chronologies and the two chronologies from the altitudinal transect (5 chronologies, 15 predictors) while the second only included the three bluff site chronologies (3 chronologies, 9 predictors). The regression results are tabulated in Table 9.5. Variance explained in the regressions varies from 21% to 58%. No verifications were undertaken at this stage. Calibrations against Amberley, Lake Coleridge and Ashburton rainfall using the tree-ring grids with seven and five chronologies, gave the best results. These six regressions are now discussed in more detail.

9.3.3 Calibration and verification, Run 2

Calibration and verification results are presented for the six regressions in Table 9.6. Verifications were undertaken for a 15 year period prior to the calibration period. Only three of the regressions verifiy significantly (r signficant at the 99.9% level and RE positive). It has been suggested that for small ($n < 20$) data sets, the RE statistic is likely to be unstable and needs to be interpreted cautiously (Jacoby and Ulan 1982). The occurrence of positive RE values in conjunction with significant r values is, however, considered encouraging here.

The regression between Amberley rainfall and the full tree-ring grid explains 46% of the variance over the calibration period. When the regression weights were applied to the verification period, 66% of the variance was explained. The RE value of 0.48 is one of the highest obtained here, a further indication of the reliability of the calibration relationship. The calibration of the full tree-ring grid against Lake Coleridge rainfall, although explaining 58% of the variance, does not verify significantly. As in the other regressions, the entry of predictors into the regression requires a t value of 1.0. In an attempt to verify this relationship, the cut-off level was increased by using a t value of 2.0 and only four predictors then entered the regression, explaining 50% of the variance. However, as in the last case, verification is not significant ($r = 0.06$, $RE = 0.99$). The regression between Lake Coleridge rainfall and the reduced tree-ring grid (five chronologies) does, however, verify significantly. 48% of the variance is explained in calibration and 44% in verification. An RE value of 0.11 was obtained. One of the regressions with Ashburton

TABLE 9.5 Run 1, summer rainfall reconstructions. Calibration of summer rainfall at five stations using three different combinations of tree-ring chronologies. All combinations include growth in years *t*, *t*-1 and *t*+1. The 50 years calibration period ends in 1974 or 1978 depending on the rainfall record.

	Chronology grid size					
	K_o[1]=21		K_o=15		K_o=9	
	K[2]	r^2[3]	K	r^2	K	r^2
Highfield	4	34	4	30	4	26
Amberley	6	46	6	35	4	28
Lake Coleridge	6	58	3	48	4	48
Ashburton	7	37	5	39	4	26
Orari Gorge	6	31	5	29	4	21[NS4]

Chronologies used: (includes growth in years *t*, *t*-1, *t*+1)

K_o = 21, GHC, LKP, RTA, LGH3, LGH6, DBT, SSS

K_o = 15, GHC, LKP, RTA, LGH3, LGH6

K_o = 9, GHC, LKP, RTA

Notes:
1. K_o - total number of predictors
2. K - number of predictors entering regression
3. r^2 - variance reduced in calibration (%)
4. NS - not significant at the 99.9% level (n-1-k d.f.)

TABLE 9.6 Run 2, summer rainfall reconstructions. Calibration of summer rainfall at three stations using two different combinations of tree-ring chronologies. All combinations include growth in years *t*, *t*-1 and *t*+1. The 50 year calibration period ends in either 1974 or 1978 depending on the rainfall record and verification is for 15 years prior to the calibration period.

Rainfall record	K_o[1]	K[2]	r_c^2[3]	r_v^2[4]	RE[5]
Amberley*	21	6	46	66	0.48
Amberley	15	6	35	64	-0.01
Lake Coleridge	21	6	58	16[NS][6]	-0.56
Lake Coleridge[7]	21	4	50	6[NS]	-0.99
Lake Coleridge*	15	3	48	44	0.11
Ashburton	21	7	37	45	0.13
Ashburton	15	5	39	15[NS]	-0.28

Notes:
1. K_o - total number of predictors (see Table 9.5)
2. K - number of predictors entering regression
3. r_c^2 - variance reduced in calibration (%)
4. r_v^2 - variance reduced in verification (%)
5. RE - reduction of error statistic
6. NS - not significant at 99.9% level (n-1-k d.f.)
7. *t* value cut off at 2.0 (see text)

* Used in final rainfall reconstructions

rainfall verified significantly, but because of the low calibration explained variance (36%) this was not used.

9.3.4 Rainfall reconstructions

The observed and estimated values for Amberley and Lake Coleridge summer rainfall are plotted in Fig. 9.4. As with the temperature reconstruction, the rainfall reconstructions have a smaller amplitude than the observed values. The nature of the rainfall-tree growth relationship causes low rainfall years (e.g. 1929, 1957, 1967 at Lake Coleridge and 1911, 1952, 1954 at Amberley) to be estimated better than high rainfall years. Once a certain amount of rainfall has fallen, soil moisture levels reach field capacity. Further rainfall does not remain in the soil, being lost as surface runoff, and is unlikely to increase tree growth further. Visually, the estimated values portray the observed values. Few major discrepancies are apparent. The observed rainfall series at both stations do not exhibit any long term trends. The regression equations developed for the calibration periods are verifiable approximations of rainfall at these two stations, especially when the distance between the rainfall stations and the tree-ring chronologies is taken into account.

The regression equations were then applied to the same tree-ring data for the period 1840-1908 (Amberley) and 1840-1912 (Lake Coleridge) and rainfall reconstructions developed. These reconstructions are presented in Fig. 9.4. The reconstructed values for the 1840-1974 (1978) period for both rainfall stations are listed in Appendix 7. The rainfall reconstructions do not extend prior to 1840 as the LKP chronology starts in 1833.

9.4 RIVERFLOW RECONSTRUCTIONS

9.4.1 Introduction

The tree-ring chronology grid used to reconstruct rainfall was also used to reconstruct Hurunui riverflow (Fig. 9.5). Riverflow, measured as mean discharge in litres per second, was reconstructed for the months when tree growth and rainfall were strongly associated; November, December and January. The short length (23 years) of the Hurunui riverflow record prevented the use of standard verification tests as the full 23 year period was needed for calibration. Alternative verification was obtained by first comparing observed riverflow for the 1956-1978 period with observed Lake Coleridge and Amberley

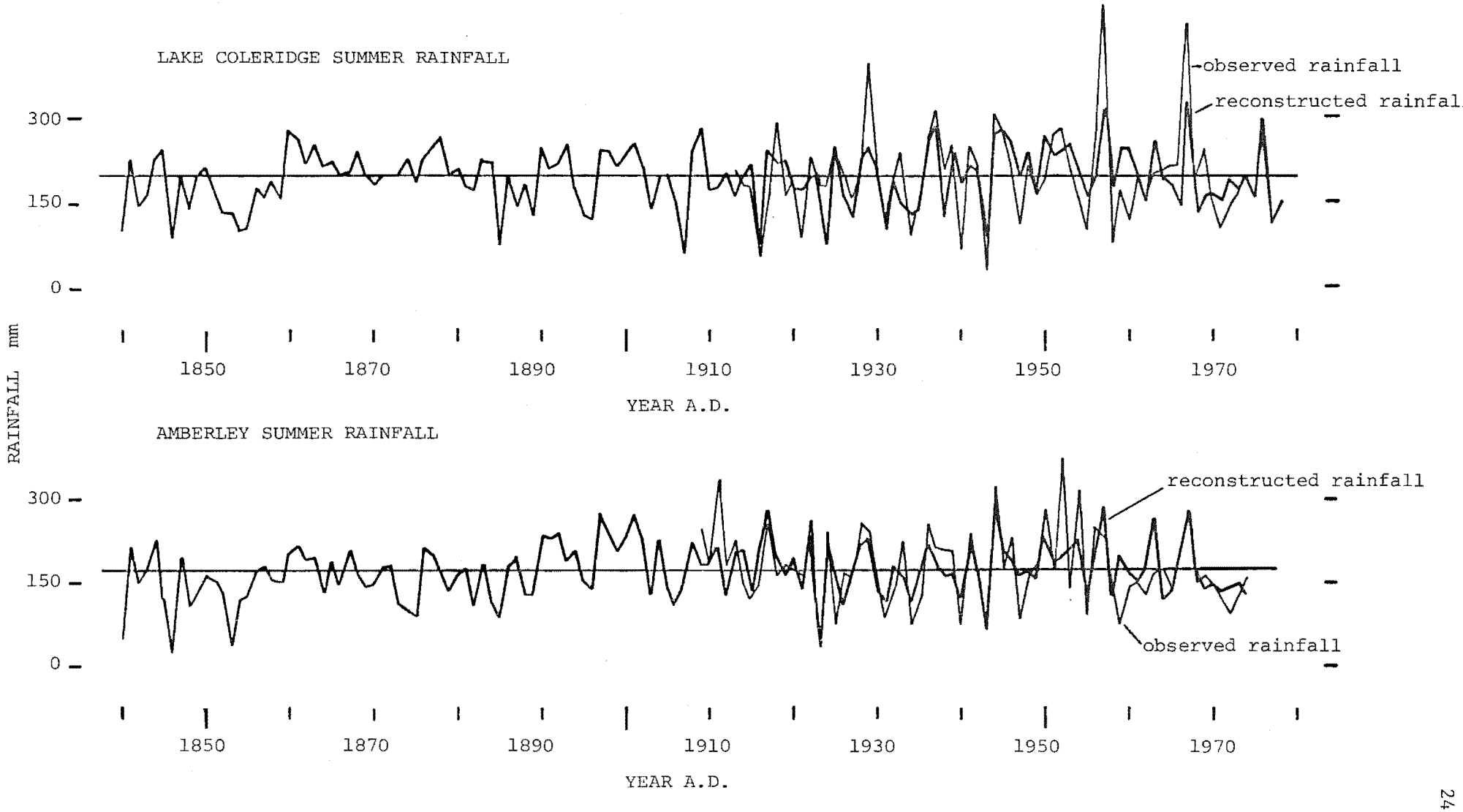


Figure 9.4 Reconstruction of Lake Coleridge and Amberley summer rainfall from 1840 to 1978 and 1974 A.D. respectively

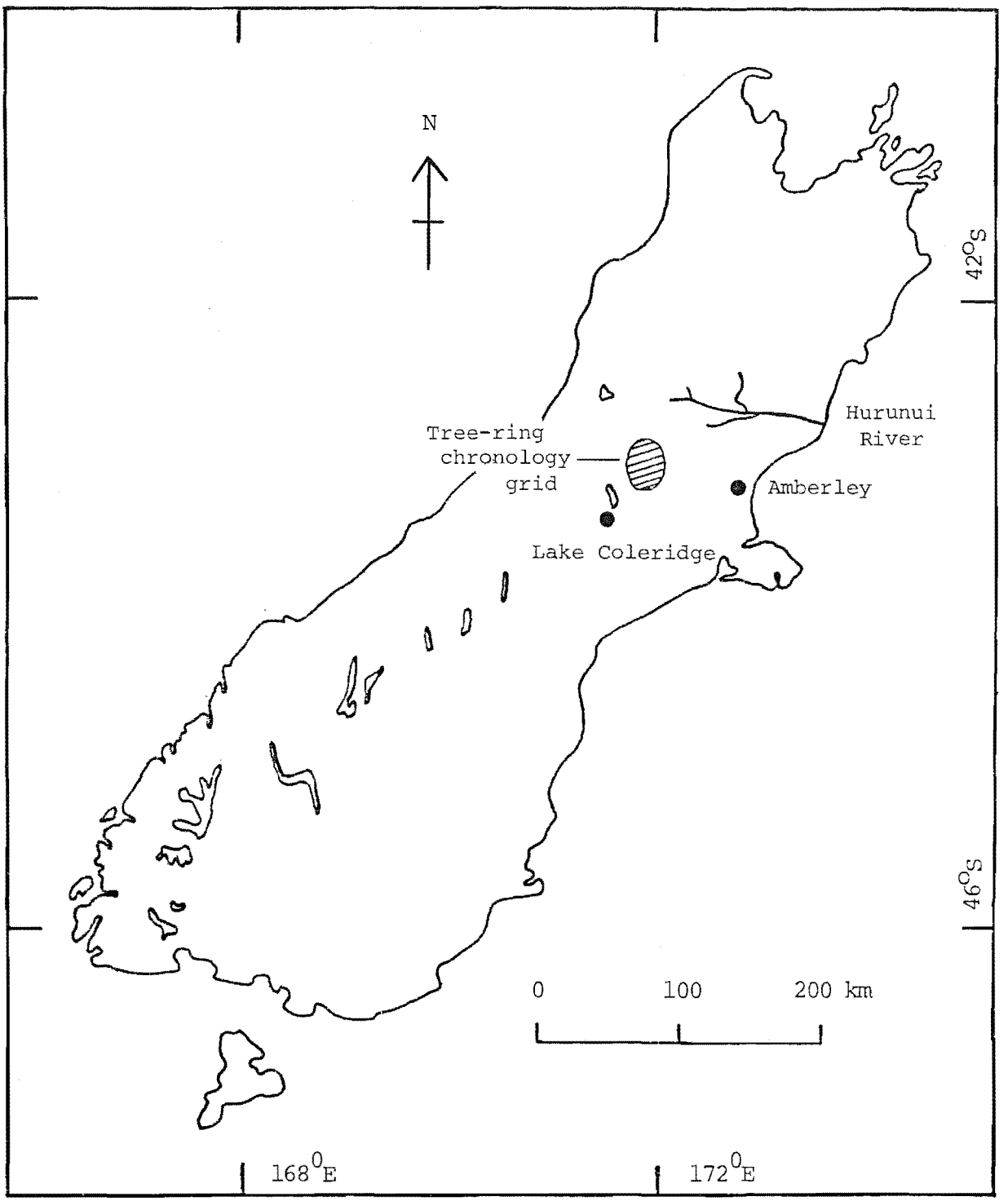


Figure 9.5 Location of the rainfall sensitive tree-ring chronology grid, Hurunui River and the rainfall stations used to verify the riverflow reconstruction.

rainfall and calculating correlation coefficients. This was then verified by comparing the estimated riverflow (from the calibration regression equation) with the observed rainfall for the 1933-1955 period. However, this is not a statistically valid way to verify the calibration relationship as it depends on a correlation with a third data set.

9.4.2 Calibration and verification

Calibration and verification results are tabulated in Table 9.7. The shortened and full tree-ring chronology grids were used in Cases 1 and 2 respectively. In Case 3 the full grid was used but with a *t* value cut-off of 2.0. Four predictors entered the regression in the first two cases, explaining 60% and 70% of the variance respectively. Increasing the cut-off *t* value to 2.0 restricted the number of predictors to two and explained variance declined to 49%. It is possible that the explained variance value of 70% could have arisen due to "artificial predictability", although the number of predictors entering the regressions was low. The correlation between riverflow and Lake Coleridge rainfall gives a significant ($P < 0.001$) r value of 0.85, while when Amberley rainfall was used, the r value of 0.52 is not significant at the 99.9% level (but significant at the 95% level). Correlations with other stations were calculated (e.g. with Hanmer Forest and Riverhead) but r values are below 0.5. As the correlation between Hurunui riverflow and Amberley rainfall is not significant, this record was not used for verification. The much stronger association with Lake Coleridge rainfall reflects a similarity in location between this rainfall station and much of the Hurunui catchment area. Both are located in the foothills of the Southern Alps, while the Amberley station is located on the Canterbury Plains (Fig. 9.5).

Two of the "verifications" with Lake Coleridge rainfall are significant (Table 9.7). Increasing the *t*-value cut-off to 2.0 in Case 3, produced a significant verification; the Case 2 verification is not significant. This confirms the earlier suggestion that there could have been some "artificial predictability" in the Case 2 calibration.

9.4.3 Riverflow reconstruction

The best verification result was obtained with Case 1 and is significant at the 99.9% level using Lake Coleridge rainfall. The r value is almost identical (to within 0.005) to that calculated

TABLE 9.7 Summer riverflow reconstructions. Calibration of summer Hurunui riverflow using two different combinations of tree-ring chronologies. Both combinations include growth in years *t*, *t*-1 and *t*+1. "Verification" is with Lake Coleridge rainfall (see text).

	Calibration (1956-1978)				"Verification" (1933-1955)
	K_o [1]	K [2]	r^2 [3]	r^2_{LC} [4]	r^2_{LC} [5]
Case 1*	15	4	60	72	72
2	21	4	70	72	17 NS [6]
3	21	2	49	72	38

Chronologies used:

Case 1* GHC, LKP, RTA, LGH3, LGH6.

2 GHC, LKP, RTA, LGH3, LGH6, SSS, DBT

3 as in Case 2 but *t* value cutoff = 2.0

Notes:

1. K_o - total number of predictors
2. K - number of predictors entering regression
3. r^2 - variance reduced in calibration (%)
4. r^2_{LC} - variance reduced in correlating observed riverflow with Lake Coleridge rainfall for the calibration period (%)
5. r^2_{LC} - variance reduced in correlating estimated riverflow, for each case, with Lake Coleridge rainfall for the "verification" period (%)
6. NS - not significant at the 99.9% level (n-1-k d.f.)

* Used in final riverflow reconstruction

between observed riverflow and rainfall during the 1956-1978 period (Table 9.7). The reasons for this similarity are unclear but the high verification value suggests that the relationship developed during the calibration period holds true for the earlier, independent period.

The calibration relationship developed in Case 1 gives the best overall result. Observed and estimated values for the calibration period are plotted in Fig. 9.6. Visual inspection of these reveals a very pronounced similarity between the two series. The high riverflows in 1957 and 1967 are well estimated, with only small discrepancies occurring.

As the observed and estimated riverflow values are similar, the calibration regression equation was applied to the tree-ring data and an estimate of annual summer Hurunui riverflow back to 1840 developed (Fig. 9.6). The reconstructed riverflow values for the period 1840-1978 are given in Appendix 7.

9.5 DISCUSSION

9.5.1 Characteristics of reconstructed series

The calibration and verification statistics presented in Sections 9.2 - 9.4 to compare the final four reconstructions with observed records, show that the reconstructions are statistically valid estimates. However, it is also necessary to consider the overall features of the series, especially long term means and variation around these. Means and standard deviations for the four reconstructions are given in Table 9.8.

Mean observed summer temperature for the 1853-1974 period was 15.9 ± 0.8°C. An increase in temperature from 15.7 ± 0.8°C in the calibration period (1853-1913) to 16.1 ± 0.8°C in the verification period (1914-1974) occurred. This difference is also present in the reconstructed series, with mean temperature increasing from 15.5 ± 0.7°C to 15.7 ± 0.6°C. As discussed above, variation is less (standard deviations smaller) in the reconstructed series. Reconstructed mean temperature is consistently lower than observed temperature (0.3°C lower overall). This difference is greatest since 1950 (0.7°C lower). The difference prior to 1900 is minor, being less than 0.02°C.

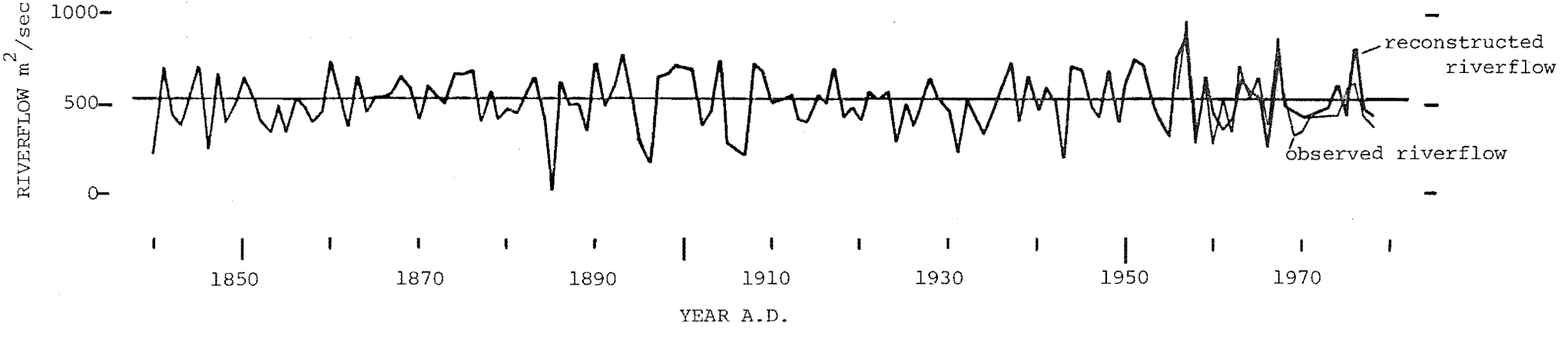


Figure 9.6 Reconstruction of Hurunui River summer riverflow from 1840 to 1978 A.D.

TABLE 9.8 Means and standard deviations of the estimated and observed temperature, rainfall and riverflow records for different time periods.

		Calibration[1]	Verification[2]	Total[3]	Reconstructed[4]	Total[5]
T[8]	obs.[6]	15.7±0.8	16.1±0.8	15.9±0.8	-	-
	est.[7]	15.5±0.7	15.7±0.6	15.6±0.6	15.6±0.7	15.6±0.6
R_A[9]	obs.	174±70	188±59	179±68	-	-
	est.	174±48	187±42	177±46	163±51	170±49
R_{LC}[10]	obs.	201±79	185±50	196±73	-	-
	est.	201±55	181±45	197±52	189±46	193±49
RF_H[11]	obs.	535±210	-	535±210	-	-
	est.	535±210	-	535±210	512±144	516±151

Notes:
1. Calibration period as defined in text
2. Verification period as defined in text
3. Combined calibration and verification periods
4. Reconstruction period as defined in text
5. Combined calibration, verification and reconstruction periods
6. obs. - observed values
7. est. - estimated values
8. T - New Zealand summer temperature (^{o}C)
9. R_A - Amberley summer rainfall (mm)
10. R_{LC} - Lake Coleridge summer rainfall (mm)
11. RF_H - Hurunui summer riverflow (m^2/sec)

These patterns are apparent in the filtered temperature series (see Section 4.3.7 for methods) with little difference prior to 1900 and greatest difference since 1950 (Fig. 9.7).

The period since 1950 has been characterised by a mean temperature increase (Salinger 1982a) which occurred in two phases; an initial increase centred around 1955 and a second increase centred around 1971 (Salinger 1981). The difference between the observed and estimated temperature series is greatest in the 1950s ($1^{o}C$ difference) and can be explained in terms of different synoptic climate conditions. The warming during the 1950's resulted from increased north to northwest airflow with maximum warming occurring in eastern areas. Easterly airflow was more important during the late 1960's and 1970's, with increased cloud in eastern areas and a strong warming in the west (Jim Salinger personal communication February 1983). Both regional airflow anomalies resulted in an increase in regional temperature but with differing spatial emphasis. Conditions associated with the second situation had a more pronounced influence on tree growth in western areas.

Despite these differences between the observed and estimated temperature series, the estimated (reconstructed) series still portrays both high and low frequency variation. The mean reconstructed temperatures for the 1730-1974 and 1853-1974 periods are identical; $15.6 \pm 0.6^{o}C$. The warmest period has occurred since 1960, although other warm periods occurred from 1770 to 1810 and from 1860 to 1880. The coolest periods occurred from 1840 to 1860 and 1910 to 1930 (Fig. 9.7). An examination of the numbers of years per decade with reconstructed temperature greater than one standard deviation below and above the mean (Fig. 9.8) shows a similar pattern. These results suggest that summer temperatures experienced since 1853 are representative of those that have occurred during the last 250 years.

In the two rainfall reconstructions, estimated values are very similar to observed values (Table 9.8) and long term trends are portrayed (Fig. 9.9). As for the temperature reconstructions, variation is less in the reconstructed series. An interesting feature of both rainfall reconstructions is a decline in mean rainfall from 177 mm (Amberley) and 197 mm (Lake Coleridge) during the calibration - verification period, to 163 mm (8% less) and 189 mm (4% less) respectively, during the earlier reconstructed period. This mean

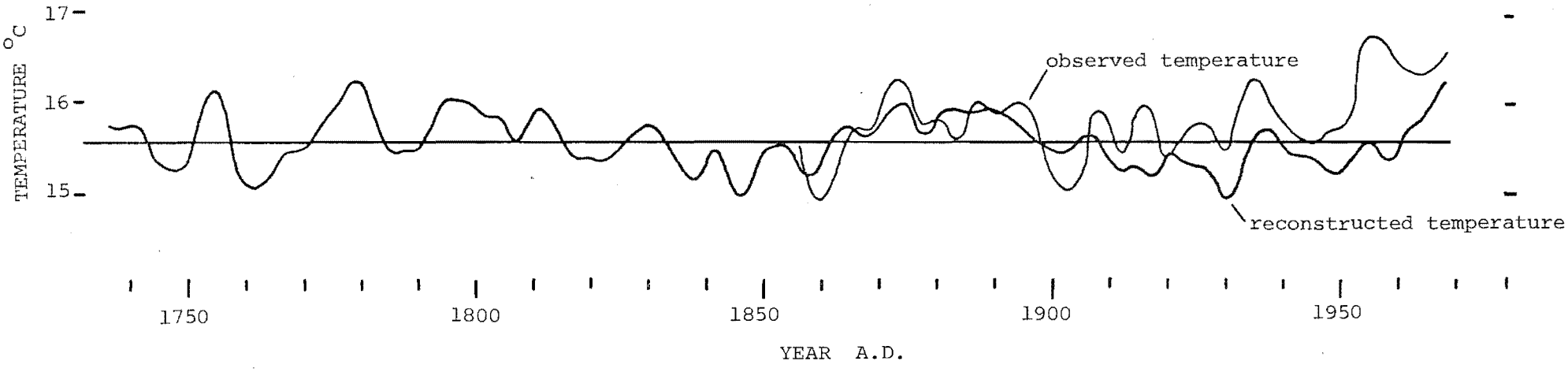


Figure 9.7 Filtered trends in observed and reconstructed New Zealand summer temperature from 1730 to 1974 A.D.

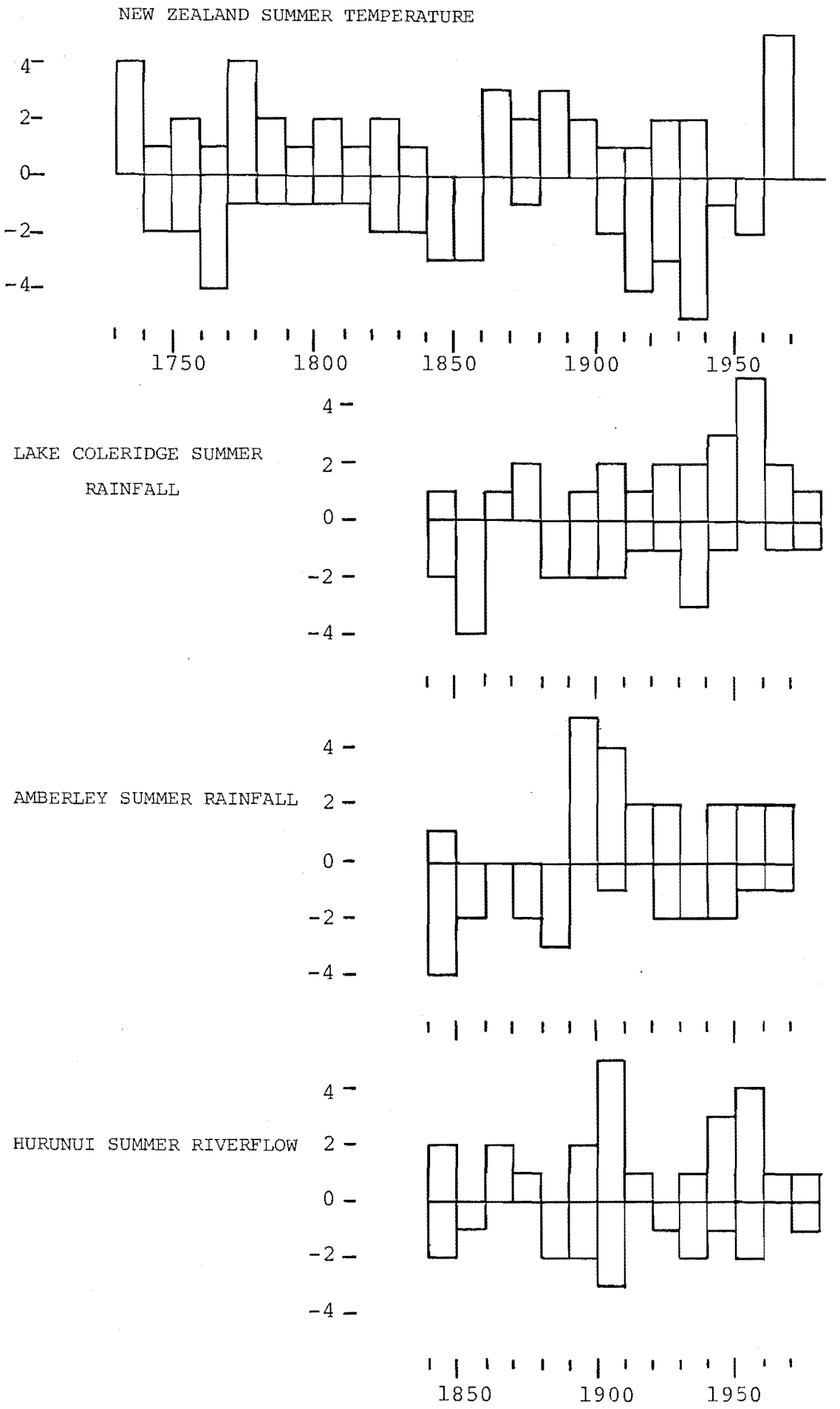


Figure 9.8 Number of years per decade when reconstructed values are greater than one standard deviation above or below the mean value for the complete reconstruction.

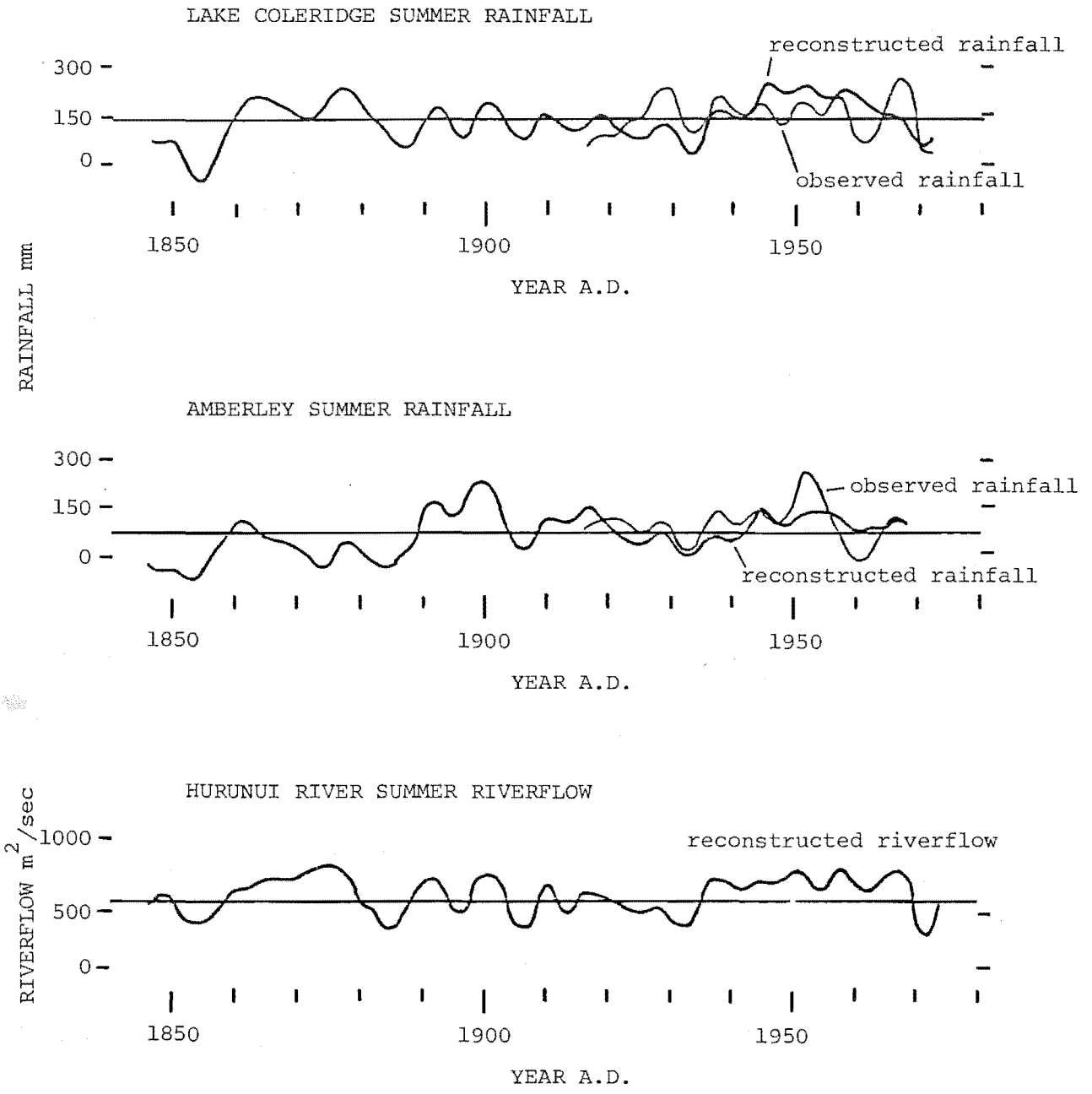


Figure 9.9 Filtered trends in observed and reconstructed summer rainfall (Lake Coleridge and Amberley) and summer riverflow (Hurunui River) from 1840 to 1978, 1974 and 1978 A.D. respectively.

rainfall decline suggests that drier conditions may have occurred during the nineteenth century. The distribution of years with rainfall significantly different from the mean are shown in Fig. 9.8. Filtered rainfall curves are shown in Fig. 9.9. The information given in these figures indicates that lowest average rainfall at Lake Coleridge occurred in the 1840's and 1850's and from 1880 to mid 1940's. Years of high rainfall were particularly common in the 1940's, 1950's and 1960's. At Amberley, low rainfall periods were more pronounced and occurred in the 1850's, 1870's and 1880's, 1900's, 1920 to mid 1940's and since 1970. Mean summer rainfall was greatest around 1900.

Few long term trends are present in the riverflow reconstruction (Fig. 9.8 and 9.9). Mean reconstructed riverflow is identical to mean observed riverflow (Table 9.8). The riverflow reconstruction gives, on average, lower estimates prior to instrumental records (1956), although high mean riverflow values similar to the recent period (1956-1978) have occurred previously (e.g. 1860's and 1870's). It is more appropriate to use the reconstructed 1840-1978 mean value as an average discharge value for the Hurunui River, than the high 1956-1978 value.

9.5.2 Historical Verification

The ability to obtain data sets that permit adequate calibration and verification are limited by the short length of available climatic records in New Zealand. The temperature record back to 1853 (Salinger 1980a) is of exceptional length compared with other New Zealand climate records. Historical records are used to verify the climatic reconstructions further. Comparison with non-historical proxy climate records is undertaken in Chapter 10.

Historical climatology is now a well established field of study. Classical studies by Ladurie (1971), Lamb (1977) and others, have shown that much climatic information can be extracted from historical records. There are many "pitfalls" in using historical records as indicators of past climates. Ingram et al. (1978) have critically discussed some of these. In some areas of the world, historical records of past climatic phenomena dating back several millenia exist. However, in New Zealand, historical records are largely confined to the period of European exploration and settlement. Most records date back to the nineteenth century. The records are unfortunately sparse and their interpretation difficult. In New Zealand, historical records

come largely from diaries and letters, travel accounts, paintings and photographs. Such records have, for example, been used to reconstruct exceptional snowfalls in the South Island high country (Burrows 1976a), to verify the early portion of the Dunedin temperature series (Salinger 1977) and to determine the extent of glacial expansion and recession in the central Southern Alps (P. Wardle 1973a, Gellatly 1982b, Salinger et al. in prep).

It was beyond the scope of this thesis to undertake a detailed search of New Zealand historical records for climatic information to verify the reconstructions. A thorough and critical assessment of these records is needed. The records cited below are examples of the type of information that is available to verify the reconstructions.

Verification for the early part of the New Zealand temperature series has been discussed by Salinger (1979a). Accounts of temperature prior to this are sparse.

John Bidwill visited the North Island of New Zealand in the early part of 1839. In the account of his travels, Bidwill (1841) records the native Maori people as saying that the 1838-1839 summer season had been one of "unusual severity" (p.32). Later, when approaching Mount Tongariro he was astonished to see the mountain snow covered and when on top (3 March 1839) he commented "The mountains in my immediate neighbourhood were all covered with snow, and much below me" (p.51). Such a snow cover is unusual during late summer but could result from an isolated storm. However, this observation and the earlier Maori observation that the summer was one of "unusual severity" are supportive of each other and suggest that mean air temperatures were considerably lower than normal. This confirms the reconstruction which estimated a mean summer temperature of 14.1^{o}C for this summer, one of the coldest summers reconstructed.

Historical records of past rainfall patterns are largely confined to observations on droughts and floods. Localised rainfall anomaly patterns (Salinger 1980b) make it difficult to extrapolate from records outside Canterbury, the location of the drought sensitive tree-ring grid. Records of floods and droughts since the 1840's have been compiled by Burrows and Greenland (1979), but they do not document the month in which the event occurred. Kidson (1931) and Bondy (1950) have discussed the occurrence of droughts during the period 1900 to 1950.

Other information on particular dry or wet seasons comes from historical records (e.g. Gilkinson 1936, Burdon 1938, Deans 1964).

The Deans brothers were amongst the first settlers to farm on the Canterbury Plains. John Dean, writing to his father on 2 September 1845, stated that "Last summer was a very different one from the preceding. We had abundance of rain, and our crops were all very good" (Deans 1964 p.39). The rainfall and riverflow reconstructions suggest that rainfall and riverflow were low for 1843-1844 and much higher for 1844-1845. The reconstructed very dry year of 1846-1847 is, however, not mentioned, although, in a letter dated 20 January 1849, the Deans brothers commented: "There has been considerable variation in the character of the weather during the summers we have been here *(since 1843)*; some of them have been very dry, and in others we have had more or less rain during almost every week" (Deans 1964 p.146). The Deans' observation suggests other dry years may have occurred during this period which, based on the reconstruction results, were possibly 1845-1846, 1846-1847 and 1848-1849.

In Central Otago the hot, dry summer of 1862-1863 (Gilkinson 1936) corresponds with low values for reconstructed Lake Coleridge rainfall and Hurunui riverflow. Amberley rainfall does not seem to have been affected. The next summer was quite different, with stormy weather until the end of December. An increase in the reconstructed values of Lake Coleridge rainfall and Hurunui riverflow are apparent. Increased rainfall associated with floods in the 1878-1879 summer in Central Otago (Gilkinson 1936), is also reconstructed.

Other historical accounts undoubtedly exist for the period up to 1900. Post-1900 records are better and the accounts of Kidson (1931) and Bondy (1950) help verify the reconstructions through to the start of instrumental records. The most noticeable feature was a drought in the 1907-1908 summer (81 consecutive days without rain in Christchurch) which is reconstructed. The reconstruction results suggest that the preceding season was also dry. Subsequent drought periods are within the calibration and verification periods.

Not all historical climatic events verify the reconstructions. A severe storm in February 1868 (Burdon 1938, Burrows and Greenland (1979) caused widespread flooding in large areas of New Zealand, but is not reconstructed here. The failure to reconstruct this event is

partly because it occurred outside the November to January reconstruction period and also because it was a single exceptional event. Not all the drought years mentioned by Burrows and Greenland (1979) for the 1889-1891 and 1897-1903 drought periods are reconstructed. The apparent failure to reconstruct all recorded events points to the need for further work on the reconstructions and also for a detailed examination of the historical records. The examples cited above show that, at least in some years, the reconstructed climate values can be verified by independent historical evidence.

9.5.3 Comparisons with other studies

Comparison of the results obtained in this Chapter (Tables 9.4, 9.6, 9.7 Figs. 9.2, 9.4, 9.6) with those obtained by other workers undertaking reconstructions, emphasise the potential of the reconstructions presented here (Table 9.9). Three other reconstructions using transfer function techniques have been undertaken in the Southern Hemisphere. Reconstruction of October to May temperature at three stations in Tasmania, using a mixed grid of *Arthrotaxis* (three), *Phyllocladus* (seven) and *Nothofagus* (one) chronologies, explained 54% to 81% of the variance in calibration. However, variance explained in verification was lower, ranging from 18% to 40% (LaMarche and Pittock 1982). Only two of the three RE values were positive and no subsample replication was undertaken.

The grid of 11 Tasmanian chronologies has also been used to reconstruct riverflow (Campbell 1982). Short riverflow records must decrease the stability of the regressions although explained variance in calibration ranged from 27% to 69%. Only three of the eight cases used records long enough for verification. Explained variance ranged from 9% to 49% in verification and two of the three RE values were positive. Using a grid of seven *Araucaria* and *Austrocedrus* chronologies in South America, Holmes et al. (1979) were able to reconstruct river-flows for two Argentine rivers, explaining 53% of the variance in calibrating both cases. No verifications were undertaken.

Many climatic reconstructions have been developed in the Northern Hemisphere using tree-ring chronologies. The very large sample grids used by Fritts et al. (1979) and Cropper (1982a) have yielded many calibrations and verifications. However, because of the emphasis in these studies on spatial climatic patterns, they are not discussed here.

TABLE 9.9 Comparison of calibration and verification statistics between this study and other recent studies.

Authors	Calibration		Verification		
	Number of calibrations	r^2	Number of verifications	r^2	Number of positive RE values
This study	4	46-60	3	44-66	3
LaMarche and Pittock (1982)	3	54-81	3	18-40	2
Campbell (1982)	8	27-69	3	9-49	2
Holmes et al. (1979)	2	both 53	0	-	-
Pilcher and Hughes (1982)	1	32	1	26	NA
Briffa et al. (1983)	8	25-58	8	13-32	7
Garfinkel and Brubaker (1980)	5	37-64	5	NA[1]	1
Jacoby and Ulan (1982)	1	47	1	37	1

Notes: 1. Three of the five r values significant at 95% level

Several modern, single station climatic reconstructions have been presented. Calibration and verification statistics for those developed since 1979 are tabulated in Table 9.9.

Pilcher and Hughes (1982) and Briffa et al. (1983) have used grids of English *Quercus* tree-ring chronologies to reconstruct rainfall and temperature. Explained variance in calibration varied from 25% to 58% and in verification from 13% to 32%. RE values were largely positive. Briffa et al. (1983) used subsample replication and obtained comparable results over the two periods. Reconstructions of temperature and rainfall in sub-arctic Alaska with a grid of *Picea glauca* chronologies explained between 37% and 64% of the variance in calibration. Three of the five verification r values were significant but only one RE value was positive (Garfinkel and Brubaker 1980). Jacoby and Ulan (1982) were able to explain 47% of the variance in calibrating a tree-ring chronology against ice conditions in Hudson Bay, Canada. 37% of the variance was explained in verification and the RE value was positive.

The percentage variance explained in calibrating the transfer functions developed in this study are similar to those developed elsewhere (Table 9.9). However, the verification statistics presented here are better than those developed in other reconstructions and confirm the earlier conclusion that these transfer functions can be used successfully for reconstructing past climates. A common feature of several of the reconstructed climate series is the reduction in amplitude compared with the observed series. The reconstructed climate series are thus conservative estimates of actual climate.

9.6 CONCLUSIONS

Four reconstructions of past climatic conditions are presented in this chapter. These are the first reconstructions of New Zealand palaeoclimate developed using transfer function techniques and show the tremendous potential of dendroclimatology for achieving this aim. The statistics developed are consistent through time and are very comparable with those of overseas reconstructions. The visual match between observed and estimated climate shows a close fit and the correlation coefficients are highly significant. Especially encouraging is the portrayal of both high and low frequency variations in the summer

temperature series. The ability to reconstruct low frequency variations suggests that considerable low frequency variance remains after standardisation in initial chronology development. However, despite the good results, it is important that these four reconstructions are interpreted judiciously as they represent the first application of a new technique to a new area and new species. Further research will undoubtedly result in the development of larger chronology grids and improved reconstructions.

PART IV

CHAPTER TEN

DISCUSSION

10.1 INTRODUCTION

Three reconstructions of past climate and one of riverflow were presented in Chapter 9. These were developed using objective statistical techniques and the reconstructions were both calibrated and verified against modern climate. Because of this, and because of the ability to date the reconstructions to the exact year, dendroclimatology has much to contribute towards our understanding of variations in past climate. These reconstructions are only first approximations and undoubtedly further research will modify them. However, they offer considerably more detailed information on New Zealand climate during the last 250 years than other proxy evidence published to date.

In the first part of this discussion, the three climate reconstructions are interpreted in terms of modern climate, particularly circulation patterns (Section 10.2) and then compared with other proxy evidence for past climates (Section 10.3). The potential use of dendroclimatological techniques to reconstruct past riverflow is discussed in Section 10.4 and the present and future application of dendroclimatology in New Zealand is discussed in Section 10.5.

10.2 CLIMATIC VARIATION IN NEW ZEALAND. I. THE TREE-RING RECONSTRUCTIONS

In this section variations in the four reconstructed series presented in Chapter 9 are discussed in relation to variations in observed climate and riverflow. The reconstructions are interpreted in terms of these relationships. In Chapter 9 it was shown that annual variations in observed climate were portrayed in the reconstructed series. Trends in climate which may represent mean shifts in climate are now considered.

10.2.1 Palaeotemperature inferred from tree-rings

The pattern of observed New Zealand temperature has been discussed in detail by Salinger (1979a, 1980a, 1981, 1982a).

Several other studies confirm his interpretations (e.g. Burrows 1976a, 1976b, Trenberth 1976a, 1977, Burrows and Greenland 1979). However, it has been suggested (Hessell 1980) that variations in observed temperature may be due to changes in the environment of the recording site (e.g. urbanisation and sheltering by trees). Although this undoubtedly occurs at some stations, other stations known to have been unaffected by such factors still show synchronous temperature variations (Salinger 1982a). Variations in smoothed New Zealand temperature (derived from filtering the annual data) are similar for maximum and minimum temperature, between the different seasons and between different regions (Salinger 1981), although the magnitudes differ slightly.

Considerable similarity is present between the estimated and observed summer temperature series (Fig. 10.1), notwithstanding the 0.3°C difference in mean values. Low summer temperatures in the 1850's and early 1860's were followed by average or above average summer temperatures from the late 1860's to the late 1890's. A rapid cooling then occurred and summer temperatures remained mainly below average until 1930. A rapid increase in summer temperature was followed by a cooling in the 1940's and a further increase since 1950. Two discrepancies occur between the observed and estimated series; one centred around 1902 and the other in the 1950's. The reasons for the latter discrepancy have already been discussed (Section 9.5.1).

A pronounced cooling centred around 1902 was not reconstructed by the tree-ring chronology grid. Low mean summer temperatures occurred in 1897-1898, 1900-1901, 1902-1903, 1904-1905 and 1905-1906 but only in 1905-1906 was the estimated value close to the observed value (Fig. 9.2). Temperature estimates for the other summers were only slightly below average. Failure to reconstruct this period is possibly related to the means by which climate influences photosynthesis. Temperature, light and vapour pressure are the main controls of photosynthesis when carbon dioxide is not limiting. It has been shown that when air temperatures are above 14°C, vapour pressure deficits are the main limit to photosynthesis in *Nothofagus solandri* trees while light is the main influence when air temperatures are below 14°C (Benecke and Havranek 1980b). Restriction of photosynthesis in trees near the alpine timberline in the South Island

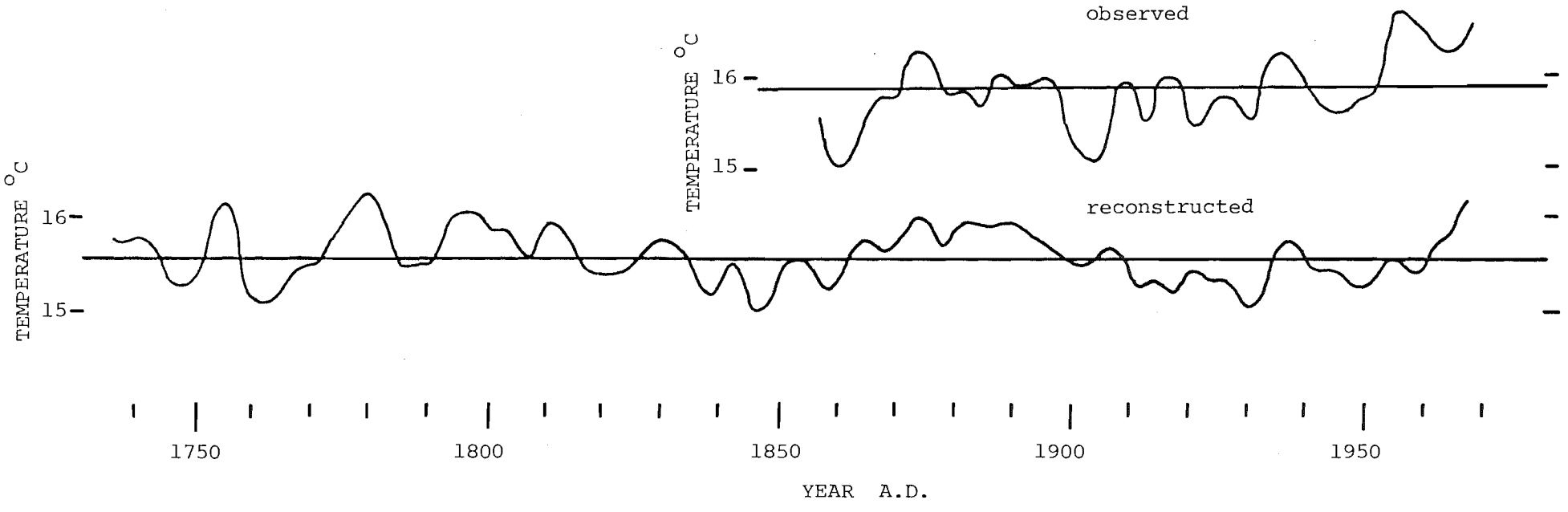


Figure 10.1 Filtered trends in observed and reconstructed New Zealand summer temperature from 1730 to 1974 A.D.

probably occurs during periods of cool stormy west to southwest airflow (e.g. 1982-1983 summer*). At such times mean New Zealand temperatures are often below average (Salinger 1980c). Cool temperatures can also occur during periods of south to southeast airflow (Salinger 1980c). At such times rainfall is highest in eastern areas (Salinger 1980b) but fine weather occurs over the central ranges and western areas (Hessell 1982). South to southeast airflow could have occurred during the period centred on 1902 with, on average, cooler air temperature. Fine weather with high light levels over the central ranges and western areas would, however, have allowed tree photosynthesis and biomass accumulation to occur. Further evidence supporting this hypothesis is presented in Sections 10.2.3 and 10.3.1.

Although some discrepancies occur between estimated and observed summer temperature since 1853, many similarities are apparent, both between annual values and between longer term trends. These similarities suggest that the reconstruction of summer temperature back to 1730 A.D. has some accuracy. This reconstruction is, however, only a first approximation and the values for summer temperature tabulated in Appendix 7 must be treated as such.

Since 1730, it seems that cooler summers occurred more commonly in the 1740's, about 1760, from 1830 to 1860, and in the first three decades of the present century (Fig. 10.1). Runs of warm summers were common about 1780, from 1790 to 1820, 1870's, 1880's and since 1960. It is difficult to accurately gauge the magnitude of these events. The cool period from 1830 to 1860 included the two coldest summers reconstructed (1838-1839 and 1845-1846) while the warmest reconstructed summers were 1730-1731, 1810-1811, 1882-1883 and

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* The 1982-1983 summer was characterised by strong west to southwest airflow onto New Zealand, especially in December, January and February, and the Southern Oscillation Index was low (Jim Salinger personal communication February 1983). Rainfall was above average in western areas and below average in the east. Temperatures were well below average in the west and average to slightly below average in the east.

1937-1938. The temperature increase from 1760 to 1780 is a particularly prominent feature, representing a 1°C increase, comparable with that occurring since 1930.

10.2.2 Palaeorainfall inferred from tree-rings

Anomalies in observed rainfall at Amberley and Lake Coleridge have not been discussed in detail elsewhere, although more general discussions of New Zealand rainfall are relevant (e.g. de Lisle 1961, Tomlinson 1976a, Burrows and Greenland 1979, Vines and Tomlinson 1980, Salinger 1980b). Rainfall in Canterbury was greatest in the 1940's and 1950's and was also above average from 1900 to 1910. Low rainfall periods occurred between 1910 and 1920, during the 1930's and since 1960 (see figure 6 in Vines and Tomlinson 1980).

Estimated trends in summer rainfall portray observed summer rainfall trends (Fig. 10.2). Conspicuous in the Lake Coleridge series is above average rainfall from 1940 to 1960 and lower values before and after this. The very wet summers of 1929-1930, 1957-1958 and 1967-1968 are portrayed less well, but excluding these the reconstruction is encouraging. Amberley rainfall was high between 1950 and 1960 and otherwise lower. Increased rainfall prior to 1920 was also reconstructed. From these results it would seem that there is some reliability in the estimated summer rainfall trends which allows interpretation of the reconstructions back to 1840 (Fig. 10.2).

Summer rainfall was below average in the 1840's and 1850's and increased in the 1860's. Summer rainfall remained high at Lake Coleridge until 1880 but was low at Amberley. Summer rainfall was high at Amberley between 1890 and 1910 but was average at Lake Coleridge and for both stations was average until a decline occurred in the 1920's and 1930's. Higher summer rainfall in the 1940's and 1950's was followed by reduced rainfall in the 1960's. The greatest difference between the two series occurred in the 1870's and 1880's and again between 1890 and 1910. These differences are probably related to differences in circulation patterns. Most rainfall at Amberley occurs during periods of southeast to northeast airflow while at Lake Coleridge westerly airflow is more important (Salinger 1981). It is possible that westerly airflow was important during the 1870's and 1880's (1878 is the most westerly year on record (Salinger 1981)) while easterly airflow was more important in the 1890's and 1900's.

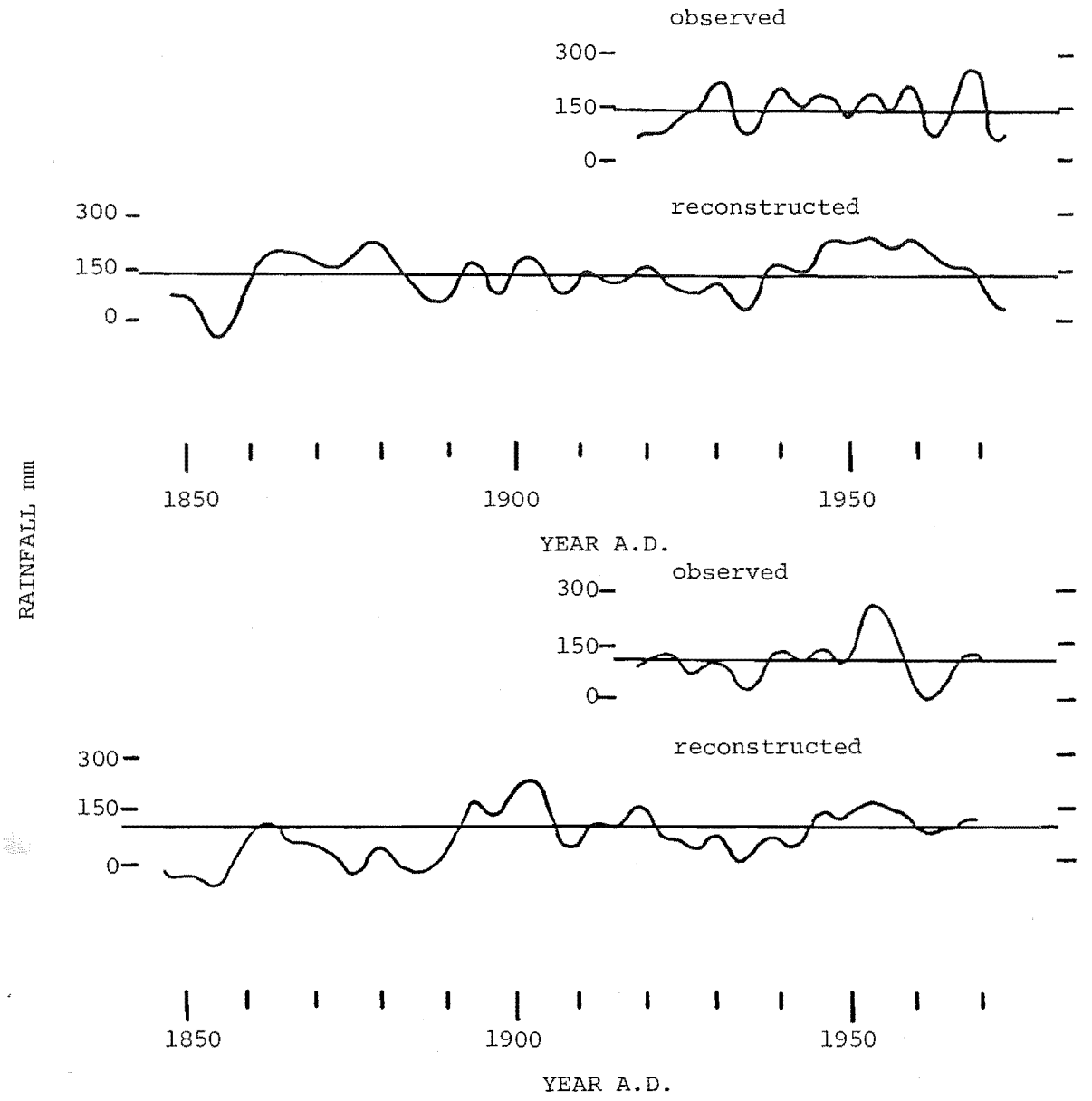


Figure 10.2 Filtered trends in observed and reconstructed Lake Coleridge and Amberley summer rainfall from 1840 to 1978 and 1974 A.D. respectively.

10.2.3 Palaeoclimates inferred from tree-rings; a synthesis

The temperature and rainfall reconstructions are now considered together in an attempt to develop an overall summary of New Zealand climate during the last 250 years. The influence of circulation patterns on New Zealand weather has been discussed in Section 1.4 and past variations in circulation patterns have been discussed by Trenberth (1977), Burrows and Greenland (1979) and Salinger (1981). Records of circulation patterns, based on pressure indices (Trenberth 1976a), only extend back to about 1920 A.D. Southerly airflow was important prior to the mid 1950's and northerly airflow occurred during the 1920's but weakened in the 1930's. Except for a short period in the 1940's, westerly airflow has remained weak. Published records finish in the mid 1970's.

For the recent period, below average temperatures have occurred during periods of predominantly westerly airflow (1920's, 1940's) and have been coldest when southerly airflow has also been important (1920's). The warming since 1950 has occurred at a time of reduced westerly and increased northeasterly airflow (Salinger 1982a). Rainfall variations since 1920 are less easily explained in terms of observed circulation patterns (Trenberth 1976a) although Salinger (1980b) found a close link between rainfall anomalies and circulation indices. Low rainfall in Canterbury prior to the 1940's occurred at a time of westerly airflow and higher rainfall in the 1950's coincides with increased northerly and easterly airflow. The decline in rainfall in the 1960's is a result of increased anticyclone persistance east of the South Island (when the Southern Oscillation index was high) giving rise to dry, mild anticyclonic northeasterly airflows (Burrows and Greenland 1979). These observations for the recent period help interpret the reconstructions.

The earlier suggestion (Section 10.2.1) of increased south to southeast airflow around 1900 is also supported by the rainfall reconstruction. Rainfall at Amberley and to a lesser extent at Lake Coleridge, was above average at this time, indicating that airflow was predominantly onto the eastern side of New Zealand. Observed summer rainfall at Hokitika was average or below average during a period of otherwise high rainfall; evidence for reduced westerly airflow.

During the 1870's and 1880's Amberley summer rainfall was low while temperatures were high. However, Lake Coleridge reconstructed summer rainfall (Fig. 10.2) and also Hokitika observed summer rainfall were high at this time. This situation suggests that north to northwest airflow predominated, giving rise to warm, moist conditions on the western side of New Zealand and dry, mild conditions in the east. Much of this rainfall would probably have reached Lake Coleridge as it is in the 'Alpine Spillover' rainfall response area (Salinger 1979b).

Low summer temperature, and low summer rainfall at both Amberley and Lake Coleridge, from 1840 to 1860 indicates that during this period cool west to southwest airflow was important, conditions perhaps analagous to the 1982-1983 summer.

The rainfall reconstructions end in 1840 and the remaining interpretation is based on the temperature reconstruction alone. Westerly airflow was probably less important between 1820 and 1770 (reconstructed summer temperatures are relatively high) but more important around 1760 and in the 1770's when summer temperatures were cooler.

The use of the two rainfall reconstructions has assisted in interpreting airflow patterns. However, these records are short. The long temperature reconstruction seems sensitive to periods of cool west to southwest airflow and has reconstructed these well. Periods of southeast airflow have been less well reconstructed. Periods of increased northeast airflow (e.g. 1930's and 1960's) have also been adequately reconstructed. This long temperature reconstruction has identified, especially, periods of cool west to southwest airflow. In the next section this record is compared with other proxy palaeoclimate evidence.

10.3 CLIMATIC VARIATION IN NEW ZEALAND. II. A GENERAL SYNTHESIS FOR THE LAST 250 YEARS

10.3.1 Other palaeoclimatic evidence

Other evidence for pre-instrumental New Zealand climate comes from a diverse range of natural phenomena. Much of the proxy climatic evidence for the last thousand years has been reviewed by Burrows and

Greenland (1979). Other reviews are given in Burrows (1982) and Salinger (1983). The evidence includes,

(i) Vegetation changes (e.g. shifts in timberline and anomalies in forest tree population structures)
(ii) Pollen analysis
(iii) Patterns of erosion and aggredation
(iv) Fluctuations in closed basin lake levels
(v) Speleothem and tree isotope ratio variations
(vi) Documented snowfall years
(vii) Changes in northern iceberg limits
(viii) Variations in glacier terminii.

This evidence, and in particular that for the last 250 years, is now reviewed briefly.

Climatic variations have been inferred from accurately dated timberline shifts in western North America (LaMarche 1973) but similar changes suggested for New Zealand timberlines (e.g. Elder 1963, P. Wardle 1973a) are not necessarily climatically caused; fire and species migration patterns are probably important. No evidence was found in the Craigieburn Range for either a shift in the altitude of timberline or for a change in the growth forms present (Appendix 2). Anomalies in forest tree population age-structures have been attributed to climatic change (Holloway 1954, P. Wardle 1963c, 1978, 1979b) but recent research (Clayton-Greene 1977, Veblen and Stewart 1980, 1982, Stewart and Veblen 1982, McSweeney 1982, Appendix 1) has suggested that these apparent anomalies reflect 'normal' stand dynamics processes. A detailed review of this subject is in preparation (Norton et al. in prep).

Pollen analysis has proved a very useful technique for evaluating changes in vegetation composition, and inferred climatic variability, over periods of thousands of years. However, the evaluation of climatic variation during the last 1000 years requires closer chronological sampling than has so far been attempted by palynologists in New Zealand. Moreover, the influence of Polynesian fire on the vegetation (McGlone 1978) is likely to present problems of interpretation.

Changes in rates of erosion and river aggredation have been inferred from various evidence in the North Island (see review in

Burrows and Greenland 1979) and have been attributed to periods of increased storminess (Grant 1981). However, the types of weather giving rise to severe storms with heavy precipitation are variable and Polynesian forest burning and tectonic events have also influenced erosion and aggredation processes.

Variations in closed basin lake levels provide a promising line of evidence for reconstructing past rainfall (Burrows 1982). Healy (1975) has shown that the recent levels of some North Island lakes are directly related to cumulative North Island rainfall. However, information for periods prior to about 1900 is sparse. Low lake levels in the seventeenth, eighteenth and nineteenth centuries have been inferred from flooded Maori sites (Healy 1975). More information is needed.

The remaining lines of evidence provide more reliable estimates of past climates.

Temperature dependent changes in the ratio between the isotopes Oxygen-16 and Oxygen-18 in calcite, from a spelothem in the north of the South Island, have been used to estimate past New Zealand temperature (Wilson et al. 1979). Dating of the proxy temperature curve was by the radiocarbon method but is considered imprecise in this case (Burrows 1982).

It has been argued that variations in the ratio of Carbon-12 to Carbon-13 isotopes are temperature dependent (see reviews in Long 1982, Wigley 1982). Variations in this ratio in an *Agathis australis* tree from the north of New Zealand have been studied by Grinsted and Wilson (1979) and a proxy temperature curve for the last 1000 years developed. Measurements were for 25 year periods. Dating of this curve is better than for the speleothem curve as tree-ring counts were made but crossdating was not used and error must still be present. Based on this curve, cool temperatures in the mid seventeenth century were followed by warmer temperatures around 1700 A.D. A cooling occurred in the mid eighteenth century, followed by a warming culminating shortly after 1800 A.D. A major cooling occurred after this. Subsequent temperature changes are not portrayed because of the increase in atmospheric carbon dioxide since 1850 A.D. (Stuiver 1978).

Years of heavy snowfall in the South Island high country since about 1860 A.D. have been documented by Burrows (1976a). When cool air associated with a strong southerly airflow onto New Zealand mixes with warm, moist northerly air already present over New Zealand, snowfalls can result (Burrows 1976a). The frequency of severe snowstorms was greater between 1860 and 1880 and between 1920 and 1940, implying that these were periods of cooler climate. Other severe snowfalls occurred in 1895, 1903, 1911, 1913, and 1918. Periods of severe snowfall were possibly periods of increased southerly airflow.

The occurrence of icebergs in latitudes further north than normal has been documented by Burrows (1976b). The record extends back to the eighteenth century. Periods when icebergs were well north included the 1770's, 1830's to 1850's, 1890 to 1910 and about 1930. Iceberg movement into lower latitudes is dependent on both ocean currents and atmospheric circulation. Periods of increased iceberg drift north could represent periods of intensified ocean currents and stronger west to southwest airflow. However, a lag in response may be present.

One of the classic approaches to the study of past climates has involved the analysis of variations in glacier terminii. The relationship between glacial behaviour and climate is complex, depending on how climate influences the glacier mass balance (the balance between snow accumulation and ablation) and how the glacier responds to changes in mass balance (Paterson 1969, Sugden and John 1976). Each glacier has its own unique response to a variable climate. The response of adjacent glaciers to the same climatic variation can be quite different, both in the lag in glacier response and in the magnitude of the response. In New Zealand these complex relations have only been investigated in detail for the Ivory Glacier (Anderton and Chinn 1978).

Moraines and other glacial deposits indicate the former extent of glaciers. Their dating can provide information on past climates. It is commonly assumed that periods of glacial advance represent periods of cooler and probably wetter conditions. Modern multivariate studies (e.g. Burbank 1982, Salinger et al. in prep) support this hypothesis and it would seem that temperature is probably the

main control. Widespread glacial recession in New Zealand since 1950 has occurred at a time of rapidly rising temperature (Salinger 1982a). Dating of glacial deposits involves a variety of techniques and in New Zealand has included lichenometry (Gellatly 1982b), rock weathering rind analysis (Chinn 1981), radiocarbon dating (P. Wardle 1973a, Burrows 1980, see also Röthlisberger et al. 1980) and historical dating (Gellatly 1982b). Other dating methods are discussed by Sommerville et al. (1982), Birkeland (1982) and Gellatly (1982b). As with any palaeoenvironment dating technique, problems occur with the different methods and have been discussed in the papers cited above.

Variations in the Franz Josef and Stocking glaciers since about 1890 A.D. are well documented (Burrows and Greenland 1979, Heine and Burrows 1980, Salinger et al. in prep) and closely parallel variations in temperature. It has been suggested that expansion of these glaciers occurred at times of cold west to southwest airflow across New Zealand (Salinger et al. in prep). A lag of between two and five years occurs in the glacier's response to climate. The cold period about 1900 was not followed by a prominent glacial advance. Although a small advance of both glaciers occurred between 1905 and 1910, it was considerably smaller than later advances (late 1920's and late 1960's) when temperatures were less cool. It is probable that atmospheric airflow was not from the southwest at this time, in agreement with the suggestion made in Section 10.2.1. Cold southeasterlies seem more likely with fine weather over the central ranges and western areas. Despite this small anomaly, the glacier record agrees well with the temperature record and suggests that dates for earlier glacier advances can be interpreted in terms of temperature (and circulation), notwithstanding differences in response time between different glaciers.

Several studies have dated glacial features formed prior to 1900 A.D. and related these to climate (see reviews in Burrows and Greenland 1979, Burrows 1982, Burrows and Gellatly 1982). The most detailed studies of recent (post 1600 A.D.) glacial fluctuations are in Westland National Park (P. Wardle 1973a) and Mount Cook National Park (Gellatly 1982b). Gellatly (1982b) has re-examined the early glacial chronology for Mount Cook National Park and revised the dating. Glacial advances at about 1640, early eighteenth century (radiocarbon date only), 1845 and 1880-1910 were recorded.

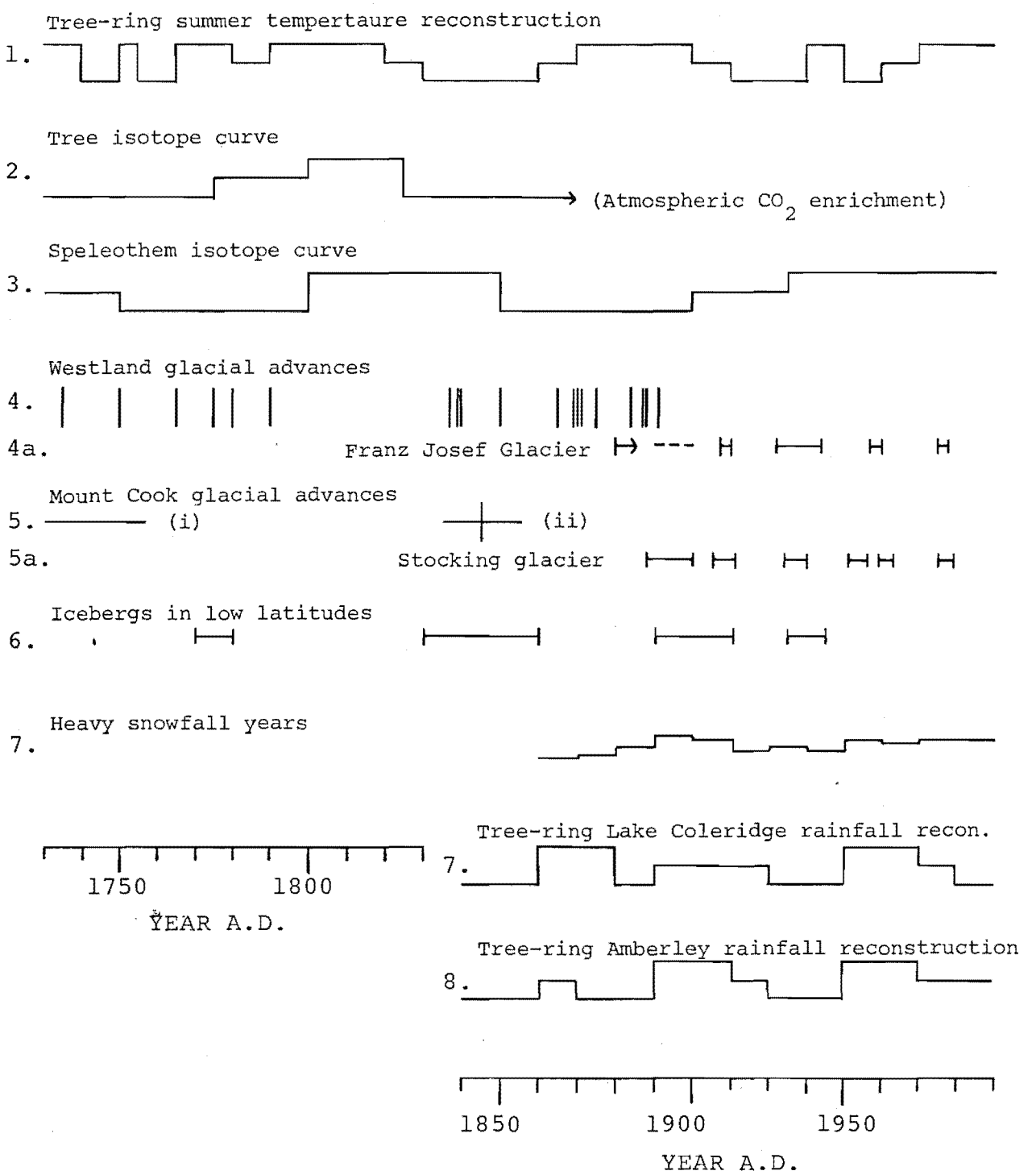
P. Wardle (1973a) suggests that three main glacier maxima have occurred since 1600 A.D., occurring prior to about 1620, 1780 and 1830 with minor advances between 1890 and 1920. Dates for the '1830' event from over half of the glaciers investigated indicate that it could have occurred later in the nineteenth century. These two studies show some agreement in the timing of glacial advances and agree with dates for glacial advances elsewhere in the South Island (Birkeland 1982, Gellatly 1982b). The synchroneity of the periods of glacial advance suggests that these periods represent periods of marked climatic variation and were possibly periods when cool west to southwest airflow onto New Zealand was strong.

10.3.2 New Zealand climate since 1730 A.D.

In the last section several different lines of palaeoclimatic evidence were discussed. There is more evidence for past temperature than for past rainfall, although some of the proxy data probably represent the occurrence of particular synoptic situations (e.g. the glaciers may respond positively to cool west to southwest airflow). However, none of these proxy data have been calibrated and verified against modern climate and the dating has a large error margin. As the tree-ring reconstructions are probably the best available for the last 250 years, they can be used to verify other palaeoclimatic evidence for this time period. A summary of inferred palaeoclimates from these other evidence and also from the calibrated, verified and accurately dated tree-ring reconstructions are presented in Fig. 10.3. Of the seven palaeotemperature records (excluding the two rainfall reconstructions), the speleothem curve is the least similar, being about 30 years out of phase with the other records. Excepting this, the different lines of evidence show a similar pattern. The different evidence are now compared with the tree-ring reconstruction.

The tree-ring summer temperature reconstruction suggests that a cool period occurred in the mid eighteenth century. The tree isotope curve is also low at this time and in Westland National Park, several glaciers advanced prior to about 1780 A.D. The only evidence from the Mount Cook region for a glacial advance at this stage is a radiocarbon date (250 ± 55 years B.P.) from the Godley Valley, dating wood buried in till (Gellatly 1982b). Glaciers in the Ben Ohau Range, Cameron Valley and Waimakariri Valley were, however, advanced at this

Figure 10.3 Summary of data drawn from phenomena which record, indirectly, climatic variations in New Zealand since 1730 A.D. The variation depicted represent only a summary of the variations recorded and interested readers should refer to the original papers for more detailed information. The different records are: 1, Tree-ring reconstruction of New Zealand summer temperature. High values are warm and low values cool. 2, Variations in carbon isotope ratio in *Agathis australis* (Grinsted and Wilson 1979). High values are warm and low values cool. 3, Variations in oxygen isotope ratio in a speleothem (Wilson et al. 1979). High values are warm and low values are cool. 4, Most recent date for the formation of moraines at several glaciers in Westland (P.Wardle 1973a). The glaciers are assumed to have reached a maximum prior to this date. 4a, Historically recorded periods of advance of the Franz Josef Glacier (Burrows and Greenland 1979). 5(i), Standard error of radiocarbon date for wood buried in till in the Godley Valley (Gellatly 1982b); (ii), Date for maximum advance of several glaciers in the Mount Cook area (Gellatly 1982b). 5a, Historically recorded periods of advance of the Stocking Glacier (Salinger et al. in prep.). 6, Periods when icebergs were sighted frequently in low latitudes. 7, Number of years per decade with exceptionally heavy snowfalls (Burrows 1976b). The more years with snowfalls, the lower the line. 8 and 9, Tree-ring reconstruction of Lake Coleridge and Amberley summer rainfall. High values are wet periods and low values are dry periods.


Tree-ring summer tempertaure reconstruction
1.
Tree isotope curve
2.
(Atmospheric CO_2 enrichment)
Speleothem isotope curve
3.
Westland glacial advances
4.
4a.
Franz Josef Glacier
Mount Cook glacial advances
5.
(i)
(ii)
5a.
Stocking glacier
Icebergs in low latitudes
6.
Heavy snowfall years
7.
1750
1800
YEAR A.D.
Tree-ring Lake Coleridge rainfall recon.
7.
Tree-ring Amberley rainfall reconstruction
8.
1850
1900
1950
YEAR A.D.

time (Birkeland 1982, Gellatly 1982b). Iceberg sightings were less common in the eighteenth century because fewer ships were present in the southern oceans than in later years. However, the 1770's were exceptional because of the number of icebergs sighted in low latitude waters.

The late eighteenth century and early nineteenth century appear to have been warmer. Both the tree-ring summer temperature reconstruction and the tree isotope record indicate warmer temperatures and there is little evidence for glacial activity at this time. Few icebergs were sighted in low latitudes between 1780 and 1830 A.D.

After about 1820, most of the proxy evidence points towards cooler temperatures. The tree-ring summer temperature reconstruction suggests that the coolest summers between 1730 and 1980 A.D. occurred between 1830 and 1860. The tree isotope curve also suggests cool temperatures at this time. Widespread glacial activity occurred throughout the Southern Alps of New Zealand during the middle of the nineteenth century. The Mount Cook glaciers were still well advanced in the 1860's when the first Europeans visited the area (Gellatly 1982b). Icebergs in low latitudes were common from 1830 to 1860 A.D. and the first decade of the snowfall record (1860's) was marked by widespread snowfalls. The instrumental temperature record, starting in 1853, records a run of cool years in the late 1850's and early 1860's. Rainfall reconstructions suggest the possibility of west to southwest airflow at this time as rainfall in eastern areas of the South Island was low.

The summer temperature tree-ring reconstruction suggests that temperatures rose again towards the end of the nineteenth century, an event, which, excepting some cold years in the 1880's, is also indicated by the instrumental temperature record. Short glacial advances in the 1890's possibly relate to the cool years in the 1880's. The summer rainfall tree-ring reconstructions suggest that rainfall was high at Lake Coleridge, but lower at Amberley, possibly reflecting the occurrence of northwest conditions. Subsequent variations in temperature have been well documented, both in this thesis and elsewhere (see various reviews cited earlier).

The similarity between the different lines of evidence discussed above suggests that some reliability can be attached to the hypothesised

climatic variations based on the tree-ring reconstructions undertaken in this thesis. However, the tree-ring reconstructions, unlike the other lines of evidence discussed, give a far more detailed interpretation of past climate. For example, the cool period in the eighteenth century probably consisted of two runs of cool years, one in the 1740's and the other about 1760. Comparison with other types of proxy climate data and with historical records (see Section 9.5.2) shows that, as well as portraying broad climatic trends, the tree-ring reconstructions provide information on shorter time-period variability. The types of airflows associated with the reconstructed climatic variations have also been suggested. However, the tree-ring reconstructions are only for summer conditions.

Based on the more detailed evidence available for past temperatures, it seems that the climatic variations occurring since European settlement (mid nineteenth century) are typical of those occurring for at least the last 250 years. The pronounced warming since 1950 (Salinger 1982a) has been suggested as the greatest in the last 2000 years (Burrows 1982). However, other warmings have occurred (e.g. from 1760 to 1780) but further study is needed to resolve the magnitude of these. Due to the short length of the rainfall reconstructions and the lack of other proxy rainfall evidence, no definite conclusions on the nature of past rainfall variations can be drawn. However, the rainfall reconstructions do show that dry and wet runs of years have occurred in the past.

The future development of tree-ring reconstructions in areas of contrasting climate (e.g. west and east coasts) will help considerably in further resolving the pattern of climatic variability in the immediate past. The prospect of longer tree-ring reconstructions is also promising (see Section 10.5). The interpretation of the reconstructions presented here and their comparison with other palaeoclimatic evidence has shown the tremendous potential and unique position of dendroclimatology as a means of developing well calibrated and accurately dated reconstructions of past climate.

10.4 HURUNUI RIVERFLOW SINCE 1840 A.D.

Rivers provide an important water resource for irrigation, hydroelectric power development, fisheries and river-based recreation. In Canterbury, irrigation is the major use of river water and has

proved invaluable for the continued development of agriculture in an area often subject to summer drought (Lewthwaite 1983). In a detailed evaluation of the water resources of the Hurunui River, Burdon (1977) has identified irrigation as the main potential use for this river. Limited irrigation schemes are already in operation.

Calculation of river water extraction limits for irrigation purposes are based on observed riverflow values. For the Hurunui River, observed riverflow records only extend back to 1956 (Burdon 1977). The possibility of extending these records further back in time is presented by dendroclimatology (e.g. Holmes et al. 1979, Campbell (1982).

The tentative riverflow reconstruction developed here (Section 9.4) illustrates how tree-ring chronologies can be used to reconstruct past riverflows. Detailed interpretation of past Hurunui riverflow variations based on this reconstruction is, at present, unwise because of unresolved reconstruction verification problems. However, it would seem that average riverflow has varied with time, probably in phase with rainfall variations.

The significance of tree-ring riverflow reconstructions is obvious, especially if, as the reconstruction suggests, average riverflow for the recent period (the period of instrumental riverflow records) has differed from the longer term average. This type of observation has important practical applications; irrigation and hydro-electric power planners are in a better position to take into account the full range of probable future riverflow conditions if long term riverflow data is available. In the tree-ring riverflow reconstruction undertaken in this thesis, the tree-ring chronologies used were not located in the Hurunui River Catchment. The use of Hurunui River Catchment tree-ring chronologies would undoubtedly improve this riverflow reconstruction considerably. This technique can be used to develop pre-instrumental riverflow records for other rivers proposed or already being utilised for hydro-electric power generation and/or irrigation development, such as the Rakaia, Waitaki and Clutha Rivers.

10.5 DENDROCLIMATOLOGY IN NEW ZEALAND

10.5.1 Strengths, weaknesses, and application to New Zealand

Dendroclimatology, like all techniques used for reconstructing palaeoclimates, has both strengths and weaknesses. Two weaknesses are particularly important.

In standardisation, flexible curve fits are used to remove growth trends and non-climatic disturbance influences from the individual tree-ring sequences (see Section 4.3.3). This makes all tree-ring sequences directly comparable and reduces the amount of non-climatic "noise" in the chronologies. However, these flexible curve fitting techniques (e.g. using polynomial curves) are unable to differentiate between growth trends and low frequency climatic trends, so that the latter may be lost from the chronology, thus reducing its usefulness as a palaeoclimatic indicator. The subjective curve fitting method used here (Section 5.2) seems to have helped alleviate this problem to some extent and differences in long term trends in tree-ring chronologies developed using different curve fitting techniques were found to be small. The presence of low frequency trends in the temperature reconstruction, similar to observed trends, is especially encouraging.

A second weakness arises because of the influence of non-climatic factors and "exceptional" climatic events (e.g. insect epidemics and snow falls) on tree growth (Section 6.7). Often these factors can cause synchronous changes in tree growth rates in many trees. Growth rate changes caused by such factors are often difficult to separate from growth rate changes resulting from shifts in average climate. This problem can be overcome to some extent by developing chronologies from several species in one area or from the same species over large areas. The use of a widely spaced tree-ring grid developed from chronologies of two *Nothofagus* species for the temperature reconstruction helped reduce the influence of these factors to some extent here.

Despite these weaknesses, the potential of dendroclimatology for reconstructing past climates is considerable. The many strengths of dendroclimatology as a palaeoclimatic indicator have been discussed in detail elsewhere. The research described in this thesis has shown that dendroclimatic techniques are applicable to New

Zealand and can be used to develop calibrated and verified reconstructions of past climate. 61 tree-ring chronologies have now been developed in New Zealand (Fig. 10.4) with nine tree species and the potential for developing further chronologies is considerable.

The application of dendrocimatology to New Zealand is greatly enhanced by the climatic sensitivity of New Zealand to fluctuations in atmospheric circulation. Lying on the northern side of the mid latitude westerly wind belt, variations in atmospheric parameters over New Zealand are also probably indicative of larger circulation changes, notably the Walker Circulation and the Quasibiennial Oscillation. The potential of New Zealand tree-ring palaeoclimatic reconstructions to act as indicators of past changes of regional atmospheric circulation systems is considerable. This is especially important as New Zealand is one of the few Southern Hemisphere land masses located in the mid latitude westerlies.

10.5.2 Future research needs

Future dendroclimatic research in New Zealand should, as a result of this work, concentrate particularly on two main areas of study; obtaining a detailed understanding of the tree-climate relationship for individual species and at individual sites and developing large tree-ring chronology grids for several species and from different site types. The second area of study also involves investigation of the potential of new species. Future research should also consider using the technique of X-ray densitometry (Schweingruber et al. 1978). This technique has the advantage that latewood density, unlike ring width, is largely independent of conditions during the previous growing season.

Possible research projects needed in the first area of study are,

(i) Investigation of the interaction between flowering and annual growth in *Nothofagus*.

(ii) Investigation of the interaction between insects and other pathogens and growth in *Nothofagus*. Study of trees in an area of known damage (e.g. the Wilberforce Valley, Canterbury high country) would be useful.

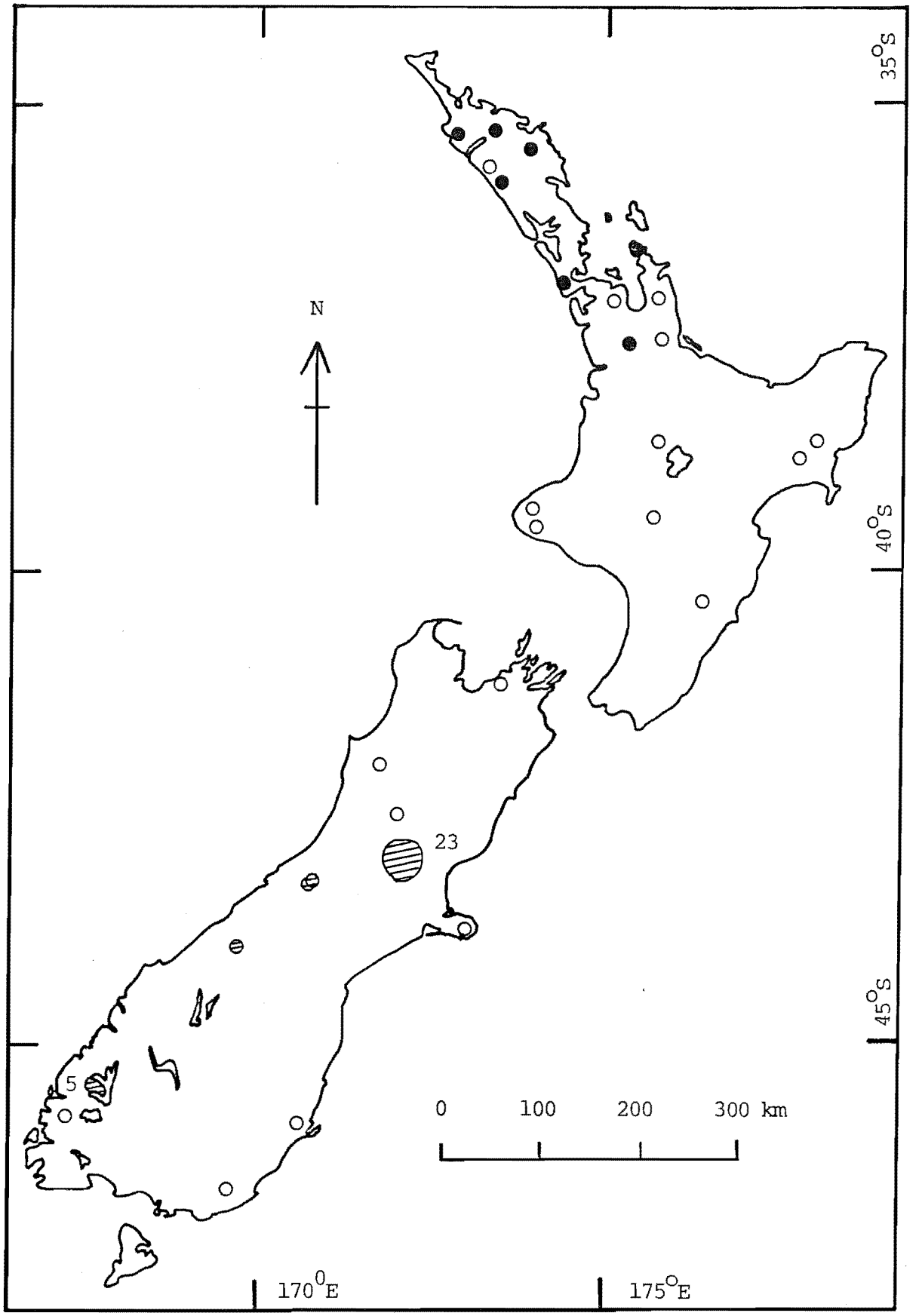


Figure 10.4 Location of New Zealand tree-ring chronologies. ● developed by John Ogden (personnal communication). O developed by LaMarche et al. (1979c). ⊖ developed in this thesis.

(iii) A detailed study of the interaction between *N.solandri* and soil moisture at montane bluff sites. The identification of substrate conditions most limiting to growth is needed.

(iv) In Chapter 5, it was suggested that there is possibly a relationship between *Libocedrus bidwillii* growth and available solar radiation. The nature of this relationship needs further study.

(v) The relationship between deforestation, drought and *L.bidwillii* tree growth on Banks Peninsula, Canterbury, warrants further study.

In the second area of dendroclimatic research, the following lines of investigation are important,

(i) The development of larger grids of temperature sensitive and rainfall sensitive tree-ring chronologies.

(ii) Investigation of the potential of other species for developing large tree-ring chronology grids.

(iii) A detailed examination of the relationship between tree growth and pressure indices using these tree-ring chronology grids.

(iv) Development of tree-ring chronology grids in the catchments of rivers proposed or already being utilised for hydro-electric power and/or irrigation development.

Presently the most suitable species for dendroclimatic research are *Nothofagus menziesii, Libocedrus bidwillii* and *Agathis australis*. Chronologies from *N.solandri* are generally too short. Future research should also concentrate on new species; *Podocarpus hallii, Dacrydium biforme* and *D.cupressinum* offer considerable dendroclimatic potential.

CHAPTER ELEVEN

CONCLUSIONS

1. Shoot and radial growth in *Nothofagus solandri* trees is closely linked to temperature.

2. Radial growth in subalpine *Nothofagus solandri* forests occurs mainly in January, February and March and there is no growth during the winter months. Growth ring formation in *N.solandri* is annual.

3. Trees within the species *Libocedrus bidwillii*, *Nothofagus menziesii* and *N.solandri* can be successfully crossdated with each other. Some crossdating is also possible between trees of *N.menziesii* and *N.solandri* but not between these and *L.bidwillii*.

4. Both circuit and vertical uniformity of ring width patterns within *Libocedrus bidwillii* and *Nothofagus solandri* trees are good.

5. The use of modern multivariate statistical techniques is essential for both chronology development and palaeoclimatic reconstruction.

6. The fitting of polynomial curves to short tree-ring series (less than 200 years long) can result in overfitting with all but the highest frequency variations being removed.

7. Differences between chronologies developed using different curve fit options in standardisation are small. This, and the portrayal of long term trends in observed summer temperature by the temperature reconstruction, suggests that the use of polynomial curves for standardisation is acceptable. However, judicious choice in curve fitting is necessary.

8. In *Nothofagus solandri* forests, trees close to the alpine timberline are more sensitive to climatic variations than

trees at lower altitudes. It can be expected that most climatic information will be retained in these tree-ring chronologies. However, trees in the timberline ecotone are less sensitive.

9. The timberline *Nothofagus menziesii* and *N.solandri* chronologies are the most sensitive to environmental variations. The bluff site *N.solandri* chronologies are less sensitive and the *Libocedrus bidwillii* chronologies are the least sensitive developed here.

10. Non-climatic factors (e.g. insect epidemics and *Nothofagus* mast years) and "exceptional" climatic events (e.g. snow falls and wind storms) can cause synchronous and widespread growth rate changes similar to those caused by shifts in mean climate.

11. *Libocedrus bidwillii* chronologies are only poorly associated with climate. This is probably in part due to the use of inappropriate climatic parameters for comparison; the relationship between *L.bidwillii* growth and solar radiation and evapotranspiration warrants further study.

12. The timberline *Nothofagus menziesii* and *N.solandri* chronologies are strongly associated with growing season temperature.

13. The bluff site *Nothofagus solandri* chronologies are strongly associated with growing season rainfall.

14. The chronologies developed here can be used to reconstruct palaeoclimates. Timberline *Nothofagus menziesii* and *N.solandri* chronologies were used to develop a reconstruction of New Zealand summer temperature to 1730 A.D. Rainfall sensitive *N.solandri* chronologies were used to develop reconstructions of Amberley and Lake Coleridge rainfall and Hurunui riverflow to 1840 A.D. The reconstructions were statistically calibrated and verified against modern climate and riverflow records.

15. The summer temperature reconstruction portrays periods of cool westerly to southwesterly airflow better than periods of southeasterly airflow. Periods of northerly airflow are also reconstructed. Cool periods have occurred in the 1740's,

about 1760, from 1830 to 1860 and at the start of the present century. Warmer periods occurred about 1780, from 1790 to 1820, from 1870 to 1890 and since 1960. The reconstructed variations in temperature help verify other proxy reconstructions of past New Zealand temperature.

16. The rainfall reconstructions appear more sensitive to periods of easterly airflow with increased rainfall at such times and to periods of increased westerly airflow when rainfall is less.

17. The reconstruction of Hurunui riverflow suggests that riverflows during the period of modern observations may have been higher than the long term average. This reconstruction and future reconstructions for other rivers presents a potentially important source of information for hydro-electric power generation and irrigation development planning.

18. This study has shown that the techniques of dendroclimatology can be successfully applied to New Zealand trees and used to develop reconstructions of palaeoclimates.

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APPENDICES

APPENDIX ONE

POPULATION DYNAMICS OF SUBALPINE *LIBOCEDRUS BIDWILLII* FORESTS, CROPP RIVER, WESTLAND, NEW ZEALAND*

A1.1 ABSTRACT

Factors influencing the population dynamics of subalpine *Libocedrus bidwillii* forests are discussed. Within the four stands studied the distribution of trees among different size-classes are dissimilar. Other studies also report dissimilar patterns and it seems that *L.bidwillii* normally regenerates intermittently. This intermittent regeneration is explained in terms of initiation of regeneration after disturbance by infrequent large-scale catastrophic events (windthrow, mass movement etc.) and/or more frequent smaller-scale gap-forming events. Release of established seedlings after small-scale forest disturbance is considered an important means of forest regeneration.

A1.2 INTRODUCTION

Forest regeneration patterns vary depending on the tree species present and the environmental conditions influencing them. In different populations of the same general forest type, one or more of the species present may have different regeneration patterns (e.g., Stewart and Veblen 1982). Forest regeneration patterns can be broadly grouped into two types.

(i) Continuous regeneration results from the steady replacement of older trees by shade-tolerant juveniles under a closed canopy, and there is an exponential decrease in the number of individuals in increasing age-classes (Leak 1975, Hett and Loucks 1976).

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* The contents of this Appendix have been accepted for publication in the New Zealand Journal of Botany and will appear in volume 21 (1983), number 2.

References cited in this Appendix are included in the main reference list of the thesis.

(ii) Intermittent regeneration occurs after conditions within the forest have altered sufficiently to allow the regeneration of otherwise suppressed or excluded species. Intermittent regeneration can occur after widespread (catastrophic) disturbance, which may result in the establishment of even-aged forests (Oliver and Stephens 1977, Veblen and Ashton 1978, White 1979). Alternatively, it can occur after smaller gap-forming disturbance events giving rise to mosaics of different aged plants and/or groups of different species composition in the main canopy of the forest (Poole 1937, Watt 1947, Williamson 1975). Populations of tree species with the intermittent regeneration mode often lack individuals in certain age-classes; such absences represent periods when gaps were not being formed.

If similar absences occur in species with continuous regeneration modes they may be interpreted as periods of regeneration failure. A paucity of smaller size-classes has been noted among the populations of trees in many New Zealand forests, especially those where podocarps are prominent (Holloway 1954, Nicholls 1956, Elder 1963, Grant 1963, P. Wardle 1963c, Burrows et al. 1975, P. Wardle 1978, 1979b). Holloway (1954), assuming that the taxa concerned regenerated continuously, explained the regeneration gaps by suggesting that anomalies in podocarp population age-structures were related to a change towards cooler, drier climates in recent centuries. P. Wardle (1963c) and Elder (1963), with the same tacit assumption about a continuous regeneration mode, proposed that this climatic change had also affected *Libocedrus bidwillii*. P. Wardle (1963c) provided data to support the regeneration gap hypothesis and concluded that regeneration was least common during the seventeenth and eighteenth centuries. P. Wardle (1973a, 1978) suggested that glacial advances at that time were evidence for a generally cooler, less sunny climate, and that this climatic change may have been responsible for the degenerate condition of subalpine *L.bidwillii* forests and for anomalies in the age-structure of other species.

Molloy (1969), Clayton-Greene (1977) and Veblen and Stewart (1980), however, have suggested that regeneration gaps are a normal feature of New Zealand forests, consequent on intermittent forest rejuvenation modes in response to disturbances of varying types and scales, rather than climatic change. In *Metrosideros-Weinmannia* forests

in Westland, disturbance ranging from small scale to catastrophic, was found to be the predominant influence on regeneration patterns (Stewart and Veblen 1982). Veblen and Stewart (1982), in a detailed study of several montane *L.bidwillii* populations in Canterbury and Westland, concluded that the regeneration of this species was also primarily controlled by natural disturbance. Although they recognised regeneration gaps there was no evidence that they were caused by climatic change. They could, however, be clearly ascribed to the regeneration behaviour of the species in relation to gap-forming events.

Several problems need to be resolved before these arguments can be settled. Do the species concerned normally regenerate continuously or intermittently? If they reproduce continually are there widespread synchronous gaps in the population structures of any of the species? If the species regenerate intermittently, synchronous or non-synchronous regeneration gaps need not be accounted for in terms of secular climate change, but periodic damaging or catastrophic climatic events may be causative of the patterns observed. This paper sets out to explore the questions posed above by examining the population dynamics of subalpine *Libocedrus bidwillii* forests in one valley in Westland.

A1.3 STUDY AREA

This study was undertaken during the 1979-1980 summer in the Cropp River catchment, Westland, South Island, New Zealand (Fig. A1.1). The geology, vegetation and climate of this area have been described in full in thesis Section 3.3.3.

A1.4 STUDY SITES

Four sites were sampled. These were chosen as discrete vegetation units representative of subalpine *Libocedrus* low forest communities, covering their altitudinal range.

(i) HUT BUSH* (HTB) (NZMS1, S64 523115) Aspect N; slope 30->50°; altitude 880-980 m; area of stand approx. 2 ha. The closed canopy at 3-5 m is dominated by *Archeria traversii* with fewer *Olearia lacunosa, O.colensoi, Coprosma pseudocuneata,*

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* Unofficial geographic name.

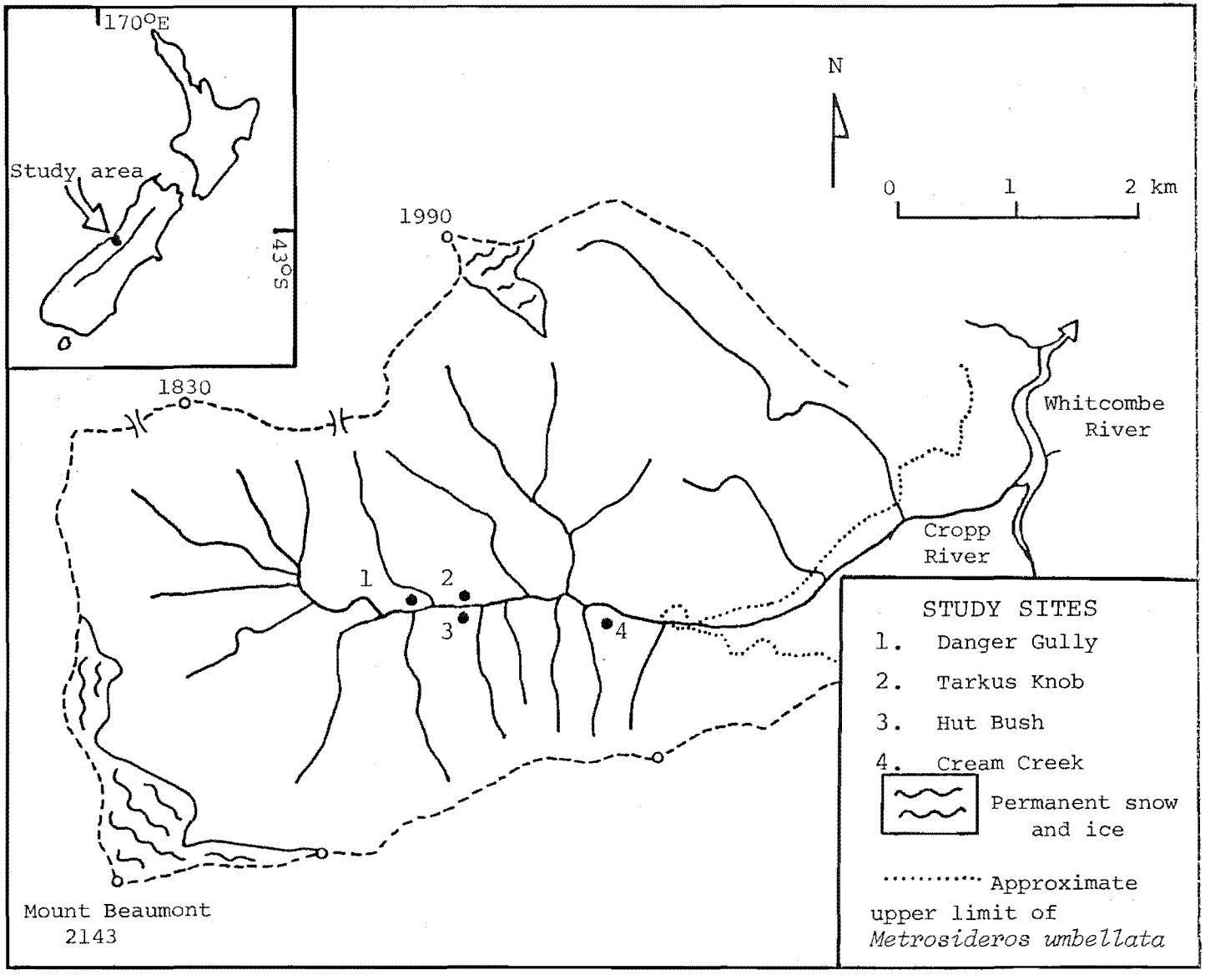

Figure A1.1 Location of study sites

Dracophyllum traversii and *D.longifolium*. *Libocedrus bidwillii*, and more rarely *Podocarpus hallii* and *Dacrydium biforme*, occur as emergents and are often of a flag form. Various shrub species, tree seedlings, herbs, ferns and bryophytes form the ground layer.

(ii) CREAM CREEK* (CRC) (NZMS1, S66 537115) Aspect N; slope 5-30°; altitude 770-870 m; area of stand approx. 1 ha. The often open canopy at 3-5 m includes *Archeria traversii*, *Dracophyllum traversii*, *Myrsine divaricata* and *Olearia ilicifolia*. *Libocedrus bidwillii*, and occasional *Dacrydium biforme*, occur as emergents. The lower branches of the *L.bidwillii* trees often contribute to the forest canopy. The *Libocedrus* trees have a tall conical shape and are rarely of a flag form. The subcanopy growth is more luxurious than at Hut Bush although the species composition is similar. *Griselinia littoralis* is abundant in the subcanopy. A variety of shrubs, tree seedlings, herbs, ferns and bryophytes form the ground layer.

(iii) DANGER GULLY (DNG) (NZMS1, S66 515119) Aspect NE; slope 20-50°; altitude 920-1000 m; area of stand approx. 2 ha. The closed canopy at 2-3 m is dominated by *Archeria traversii*, *Dracophyllum longifolium* and *D.traversii*, the latter in places completely excluding the others. Little understorey or ground vegetation occurs under pure *D.traversii* stands because of the very deep litter of undecomposed leaves. *Libocedrus bidwillii* and occasional *Dacrydium biforme* occur as emergents; near the spur crest they become stunted and *Phyllocladus alpinus* also occurs in the canopy.

(iv) TARKUS KNOB* (TRK) (NZMS1, S66 523117) Aspect SW; slope 20-40°; altitude 880-940 m; area of stand approx. 2 ha. An almost pure *Olearia* low forest community, with rare emergent *Libocedrus*. A low canopy at 1.5-2.5 m consists of *O.colensoi* and *O.lacunosa*, with some *Dracophyllum longifolium* and *Coprosma pseudocuneata*. *Dracophyllum traversii* is emergent. The ground layer is sparse and no *L.bidwillii* seedlings were seen.

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* Unofficial geographic names.

Other subalpine sites with *L.bidwillii* appear similar in composition and structure. Soils differ considerably within the stands but tend to be young and weakly gleyed. The Hut Bush, Danger Gully and Tarkus Knob sites occupy steep faces well above the present river levels in the upper parts of the valley (Fig. A1.1) and were formed by mass wasting. The Cream Creek site is on an aggradational surface formed by mass movement after ice retreat. At all sites evidence of recent disturbance (slips) is prominent.

A1.5 METHODS

Mean diameter at 1 m above ground (d1m) of all trees taller than 1 m was recorded and the data sorted into 10 cm size classes. From all trees without extensive rot two cores were removed using an increment borer. The height of seedlings was recorded. Five seedlings were cut to determine the time taken to grow to 1 m.

Libocedrus bidwillii tends to form discrete populations in the Cropp Valley and an attempt was made to sample every tree within the populations studied. This was achieved at the DNG and TRK sites where 83 and 21 trees respectively were sampled. At the CRC and HTB sites all the trees (101 and 176 respectively) in large representative proportions of the stands were sampled. Plots of definite size and shape were not used because of the very steep and varied topography of the sites. While measuring adult trees and traversing elsewhere in the stands, all seedlings encountered were recorded. The seedling counts are considered a representative and almost complete census of the total seedling populations.

The cores were air-dried and glued, transverse surface upwards, onto grooved wooden blocks which provided strong permanent mounts. Good surfaces for counting the rings were obtained by sanding the cores and discs with successively finer grades of sandpaper until the cellular detail of the rings could be seen clearly. A binocular microscope, set at low magnification (x10), was used for counting the rings. The growth rings of *Libocedrus bidwillii* are believed to be annual (P. Wardle 1963b). Crossdating of ring patterns between trees for dendroclimatological analysis (Chapter 5) confirmed the annual nature of the growth rings. Crossdating also helped identify missing and false rings, thus ensuring accurate age determinations.

Linear and logarithmically-transformed regressions of age and diameter data were used to test the assumption that diameter is a good predictor of tree age. *Libocedrus bidwillii* tree measurements and seedling data from the four sites were organised into 10 cm size-classes and the frequency distribution among the size-classes analysed. Quantitative analysis of the size-class distributions was based on the goodness-of-fit to the distribution described by the power-function model, which Hett and Loucks (1976) have suggested adequately describes the structure of all-aged tree populations. The power function model is

$$y = y_o x^{-b}$$

where y is the number of trees in any size class x, y_o is the initial input into the population at time zero and b the mortality rate.

A1.6 POPULATION SIZE STRUCTURES

Heart rot occurred in 68% of all trees making it difficult to establish population age distributions, a problem also noted by Dunwiddie (1979). For the sound trees, linear regressions between tree diameter and age suggest that diameter can be used as a predictor of age ($r = 0.71$-0.90, $P<0.001$) (Fig. A1.2). Logarithmically-transformed regressions were also significant ($P<0.001$), but less so than the linear regressions. The wide variation of age within any one size-class (often over 200 years) considerably reduces the accuracy of age estimates from diameter measurements. For this reason no attempt was made to date regeneration patterns.

Mean growth ring width was 0.64 mm. Many rings were either absent (inferred from crossdating) or very small, consisting of only one or two rows of cells. Unless sections and cores are properly prepared by sanding and carefully examined under a microscope, and crossdating techniques employed (Stokes and Smiley 1968), it is probable that most tree age counts will be underestimates.

The mean age, at 1 m, of the five cut seedlings was 65 years. The range, 35-103 years, reflects differences in microsite conditions, especially light intensity. This large range further highlights the problems in making age estimates from diameter data for this species.

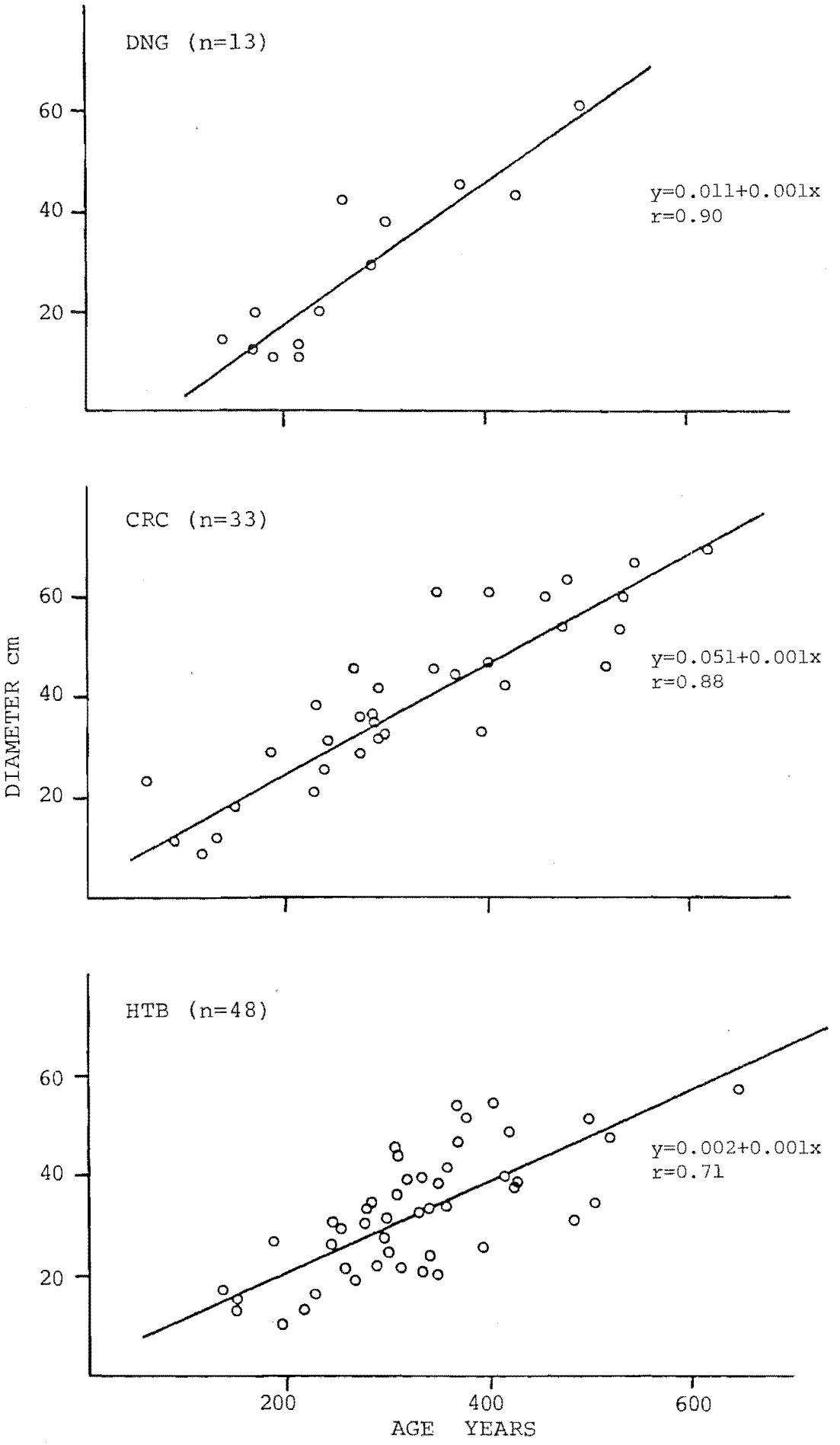

Figure A1.2 Relationship between age and diameter of *Libocedrus bidwillii* trees at the DNG, CRC and HTB study sites

Fig. A1.3 gives size-class diagrams for the four sites. Goodness-of-fit tests between these and the distribution described by the power-function model show no significant agreement for the CRC and HTB sites but the DNG site is significantly in agreement ($P = 0.010$). The sample size at the TRK site was not large enough to test. The number of seedlings in successive classes declines with increasing height-class (Fig. A1.4). The size-class distributions for the four sites appear, on visual inspection, to be dissimilar. Only at the DNG site are all tree sizes present in the population. At this site seedling numbers are also higher and it seems that seedlings are being recruited into the adult population. Although seedlings occur at the CRC and HTB sites none are present in the 0.8 - 1.0 m height-class and smaller sized stems are rare. At the TRK site no seedlings or young stems are present. Dead stems are abundant at the HTB site, especially in the larger size-classes.

A1.7 DISCUSSION

It has been suggested by Holloway (1954), P. Wardle (1963c, 1978) and others that there has been a widespread, and possibly synchronous, failure in the regeneration of several New Zealand gymnosperm species, including *Libocedrus bidwillii* (see review in Burrows and Greenland 1979). Evidence presented here and in other papers (Clayton-Greene 1977, Veblen and Stewart 1982) conflicts with this view. The size-class distribution in the populations examined here are dissimilar; at only one site (DNG) are small trees common. Clayton-Greene (1977) and Veblen and Stewart (1982) also found that although smaller size-class stems were lacking at some sites they were abundant elsewhere, especially in recently disturbed sites. P. Wardle (1963c, 1978) found a paucity of smaller size-class *L.bidwillii* stems at several sites although other size-classes were adequately represented. The populations examined in these five studies do not show synchronous failures or pulses of regeneration. It is therefore unnecessary to consider regional (i.e. climatic) mechanisms to explain the population dynamics of these forests.

Libocedrus bidwillii seedlings in the subalpine forests of the Cropp River catchment frequently grow on steep banks and spur crests, where the understorey vegetation is less dense. Presumably light intensities on the forest floor are higher here than in forests on

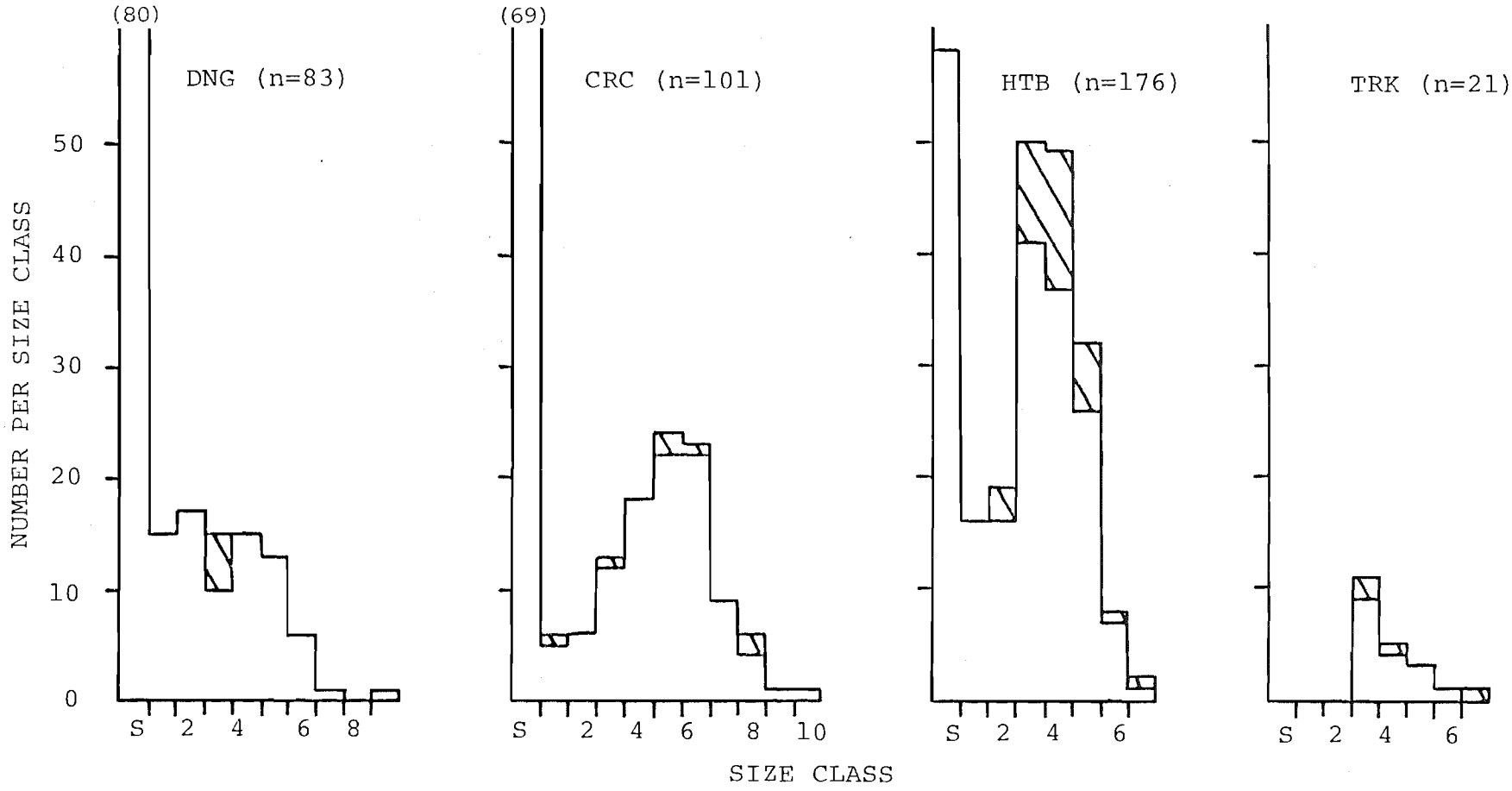

Figure A1.3 Size-class distributions of *Libocedrus bidwillii* trees from the four study sites. The size classes are; S, seedlings (i.e. less than 1 m tall); 1, trees of dlm 0-10 cm; 2, trees of dlm 11-20 cm; etc.

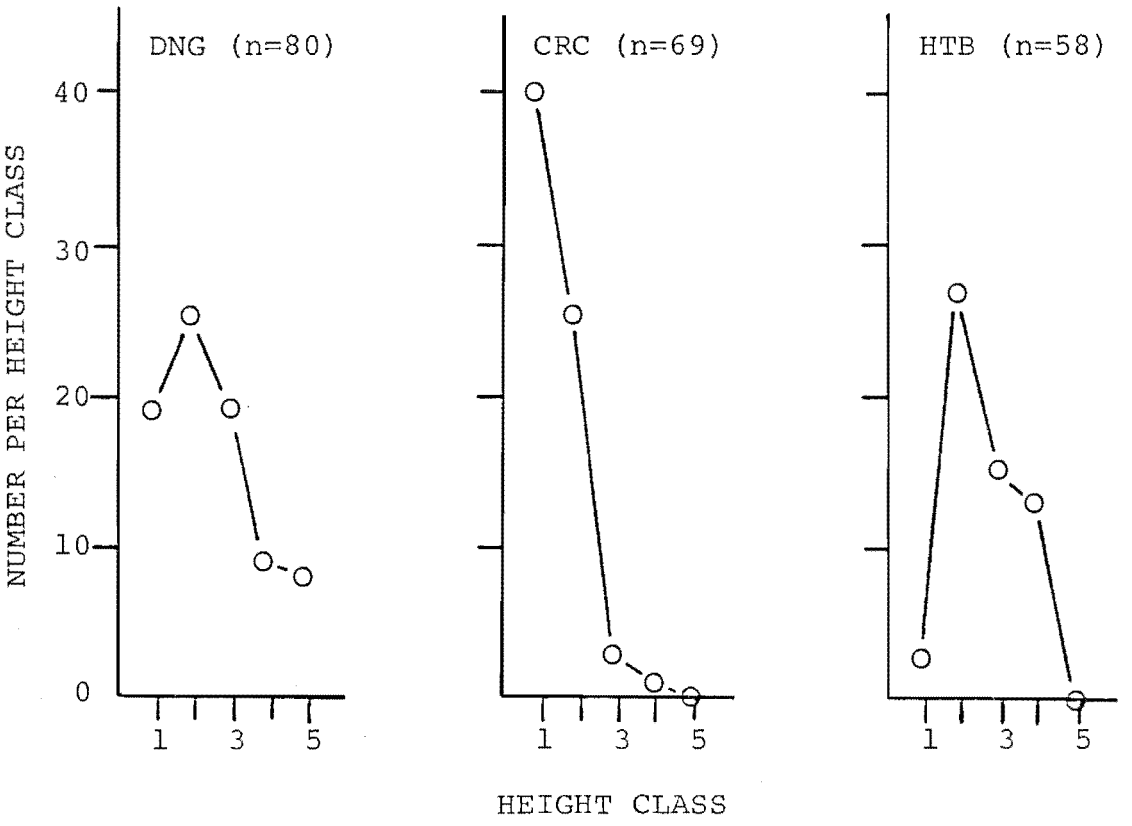

Figure A1.4 Height-class distribution of *Libocedrus bidwillii* seedlings from the DNG, CRC and HTB study sites. The height-classes are; 1. 0-20 cm; 2. 21-40 cm; etc. n = number of seedlings.

more gentle slopes. Seedlings were not seen under dense low scrub. *L.bidwillii* is regenerating freely on thin, gleyed soils and in open stunted vegetation dominated by *Dacrydium biforme* near the TRK study site. In other *L.bidwillii* forests similar regeneration patterns have been reported. On Banks Peninsula, *L.bidwillii* seedlings are confined to the forest margins (P. Wardle 1978, D.A.N. personal observation) and on Mount Cargill (Otago) *L.bidwillii* regeneration is abundant amongst open scrub (personal observation). Johnson et al. (1977), P. Wardle (1978) and Veblen and Stewart (1982) also note abundant *L.bidwillii* regeneration in open, stunted vegetation on soils with impeded drainage. The apparently reduced light levels associated with compact subalpine forest canopies and dense subcanopy scrub layers appear to inhibit regeneration of *L.bidwillii*. The regeneration requirements of this species would therefore seem best explained in terms of reduced shading during establishment of seedlings and at later stages in their growth through the subcanopy and canopy vegetation.

The predominantly young ages and varied nature of the soils under *Libocedrus bidwillii* and other forest types in the Cropp River catchment suggest the occurrence of frequent disturbance. The stands examined in this study have probably been subjected to a range of disturbance events, from infrequent catastrophic events to more regular, smaller gap-forming events. Many factors including fire, windstorm, icestorm, landslide, snow avalanche, flooding, browsing and disease may initiate regeneration. Windthrows were recognised in the subalpine forests examined and seedlings were observed at one recent windthrow at the CRC site. Release of established seedlings after windthrow is probably an important aspect of *L.bidwillii* regeneration in these subalpine forests. Many slips of varying size, age, and vegetation development, were noted in the subalpine forests investigated. During fieldwork some slips were observed to have occurred after heavy rain. The deposition of debris associated with flooding has probably been important at the CRC site. Streams at this site are likely to change course during flooding causing forest disturbance. Layers of sand and schist debris above mature soil at this site are evidence of such stream course changes. Clumping of trees of similar size commonly occurs at all sites and represents seedling establishment or release of already present seedlings after smaller disturbance events. The *L.bidwillii* stands at the steep HTB and DNG sites could have become

established after earthquake initiated mass movement. Heavy rain may also have initiated mass movement on these steep hill sides in the past.

Frequent disturbance appears to be a feature of subalpine and montane forests in New Zealand. Massive disturbance from windthrow has initiated *Libocedrus bidwillii* regeneration on Mount Te Aroha and Mount Pirongia in the Waikato district (Clayton-Greene 1977). Grant (1963) suggests that a large storm occurring in the Urewera mountains during the seventeenth century felled large areas of forest. *Nothofagus* forests frequently show evidence of widespread windthrow (e.g. J. Wardle 1970d, Norton and Wilson 1981). In the Poulter River Valley, inland Canterbury, many hectares of *N.solandri* forest, from valley floor to near timberline (an altitudinal difference of 500 m), have been affected recently by windthrow (personal observation). P. Wardle (1978) noted the establishment of *L.bidwillii* seedlings after windthrow and also at the top of a landslide in South Westland. Stewart and Veblen (1982) document widespread windthrow in Westland *Metrosideros umbellata - Weinmannia racemosa* forests and also abundant regeneration of these species on sites devastated by landslides. Even-aged stands of *M.umbellata* and *W.racemosa* forest on steep faces in Westland National Park may have been initiated by an earthquake in the eighteenth century (P.Wardle 1980b). There is a similar stand of *M.umbellata* in the lower Cropp (NZMS1 S64 545113). Elder (1963) suggests that fire has stimulated *L.bidwillii* regeneration in the North Island. On Mount Cargill (Otago) *L.bidwillii* regeneration has occurred after fire (personal observation).

A1.8 CONCLUSIONS

The structure of the *Libocedrus bidwillii* stands examined here are explicable in terms of intermittent regeneration, similar to that described by Clayton-Greene (1977) and Veblen and Stewart (1982). Disturbance renders sites suitable for seedling establishment or releases already established seedlings. Various degrees of disturbance occur, ranging from the toppling of individual trees, to widespread forest destruction by mass movements and other processes. In the present study, the results of smaller disturbance events were more frequently observed than catastrophic disturbance influences and may account for many of the vegegation patterns observed. These smaller-

scale events (localised windthrows, slips, debris flows, or other similar phenomena) result in the death of an individual or small group of trees. Frequent clumping of trees of similar size, and the occurrence of many slips of various ages and of small windthrows, are evidence of gap-phase regeneration in the subalpine forests studied. The paucity of smaller size-class stems at some sites in part reflects a lack of recent disturbance, and also the need for only occasional recruitment of seedlings of the long lived *L.bidwillii* trees to maintain populations at present levels. Disturbance is the main initiator of intermittent regeneration of *L.bidwillii* in the subalpine forests investigated and has a pronounced influence on the population dynamics of these forests.

APPENDIX TWO

NOTHOFAGUS SOLANDRI GROWTH FORMS AT THE ALPINE TIMBERLINE, CRAIGIEBURN RANGE, NEW ZEALAND*

A2.1 ABSTRACT

The growth forms of *Nothofagus solandri* trees at the alpine timberline in the Craigieburn Range, Canterbury, New Zealand, are described. These forms arise in response to winter conditions; the effect of wind and snow being particularly important. The main processes recognised as modifying tree growth are foliage death and shoot dieback, stem deformation and coppicing. Vegetative proliferation is more important at timberline than at lower altitudes. Many timberlines lacking stunted growth forms have developed in response to fire. Those which are not caused by fire are diverse with several distinctive growth forms present. It is concluded that although the timberline ecotone in these angiosperm forests is very narrow compared to those of Northern Hemisphere gymnosperm forests, the climatic conditions experienced in the timberline ecotone modify and deform tree growth in a similar manner.

A2.2 INTRODUCTION

The alpine timberline, the zone where forest is replaced by alpine vegetation, is a major ecological boundary. In many parts of the world, forest gives way gradually to alpine vegetation through a broad transition zone, the kampfzone or timberline ecotone (Tranquillini 1979). In this ecotone trees become reduced in stature, at the highest altitudes often to the extent of forming cushions close to the ground, before being replaced by alpine vegetation. The upper part of this ecotone, where the trees are very stunted, is called the krummholz zone. Holtmeier (1981) differentiates between environmentally

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* The research described in this Appendix benefited considerably from field excursions and discussions with Dr Walter Schönenberger of the Swiss Federal Institute of Forestry Research. A joint publication is presently in preparation.

References cited in this Appendix are included in the main reference list of the thesis.

determined and genetically determined dwarf trees, applying the term krummholz to the latter only (e.g. *Pinus mugo* var. *prostrata).* In this paper, however, krummholz is used in its wider sense applying to all stunted and dwarfed trees in the timberline ecotone. Outside the tropics, the limitation of tree growth with increasing altitude is due primarily to the inability of trees to complete summer growth with subsequent death because of winter desiccation and frost damage (Tranquillini 1979). This is particularly important during the seedling stage (P. Wardle 1971).

The physiognomy of timberlines varies depending on the response of the species present to environmental conditions and anthropogenic influences. *Nothofagus* timberlines are remarkably abrupt and level, commonly lacking the distinctive krummholz zone of the Northern Hemisphere. The ability of *Nothofagus* trees to form such a sharp boundary is a consequence of the better performance of the shade tolerant seedlings, especially their survival through the first year within the forest rather than in the open grasslands (P. Wardle 1971). Considerable modification of the environment occurs within the forest compared with adjacent grassland (Tranquillini 1979), and forest is able to ascend to the maximum altitude at which tree growth can be completed.

Superimposed on this broad pattern of an abrupt limitation of *Nothofagus* tree growth there is also a more subtle variation in the position of local timberlines and especially of the growth forms present. This second pattern is dependent on local factors and relates particularly to winter conditions. Quite striking differences in tree growth forms can be found over short distances at timberline. Although a krummholz zone, as such, is unusual in New Zealand *Nothofagus* forests, krummholz growth forms develop at timberline where snow accumulates on the forest margin. When a distinctive krummholz zone is present, it represents a depression of the forest limits, rather than forming a band above the limit of erect trees as occurs at many Northern Hemisphere timberlines. In favourable sites nearly erect *N.solandri* trees can be found at some of the highest points of the timberline. Studies in the Northern Hemisphere have shown that a large variety of growth forms occur in the timberline ecotone and that they are caused by wind and snow (e.g. Yoshino 1973, Holtmeier 1980, Schönenberger 1978, 1981) as well as biotic and other factors. Although several

different growth forms have been described for *N.solandri* timberlines (Conway 1977, J. Wardle 1970c, P. Wardle 1963b, 1965, 1971) no attempt has been made to systematically classify the main forms present. It is the aim of this research to do so and also to elucidate factors causing the different forms.

A2.3 STUDY AREA

This study was conducted in the Cass, Hamilton, Craigieburn and Broken River catchments of the Craigieburn Range (Fig. A2.1). This range is located 20 km east of the main divide of the Southern Alps in Canterbury, New Zealand and forms part of the watershed between the Rakaia and Waimakariri Rivers. The geology, vegetation and climate of this area have been described in full in thesis Section 3.3.1.

A2.4 METHODS

No attempt has been made to quantitatively describe all the different growth forms. Rather, distinctive growth forms were identified and possible processes affecting tree growth at the alpine timberline determined. The timberlines were visited in summer and winter from 1980 to 1982. Transects 5 m wide and of different length were placed through different timberlines and branching patterns of the trees were mapped.

A2.5 TIMBERLINE TREE GROWTH FORMS

Due to often severe environmental conditions at the alpine timberline (frost, winter desiccation, mechanical forces) trees are commonly damaged. Damage affects different parts of the tree (foliage, buds, stems) and occurs in different ways. When trees recover they react distinctively giving rise to several different growth forms. At the alpine timberlines in the Craigieburn Range, six distinctive *Nothofagus solandri* growth forms can be recognised (Fig. A2.2). *N.solandri* growth forms associated with avalanche paths are considered elsewhere (Conway 1977, Burrows et al. 1980).

A2.5.1 Prostrate growth form (Fig. A2.2a)

Prostrate growth form trees typically have gnarled boles with many twisted and contorted stems and a low canopy approximately 20 cm to 30 cm above the ground at the upper edge and not more than 2 m at the

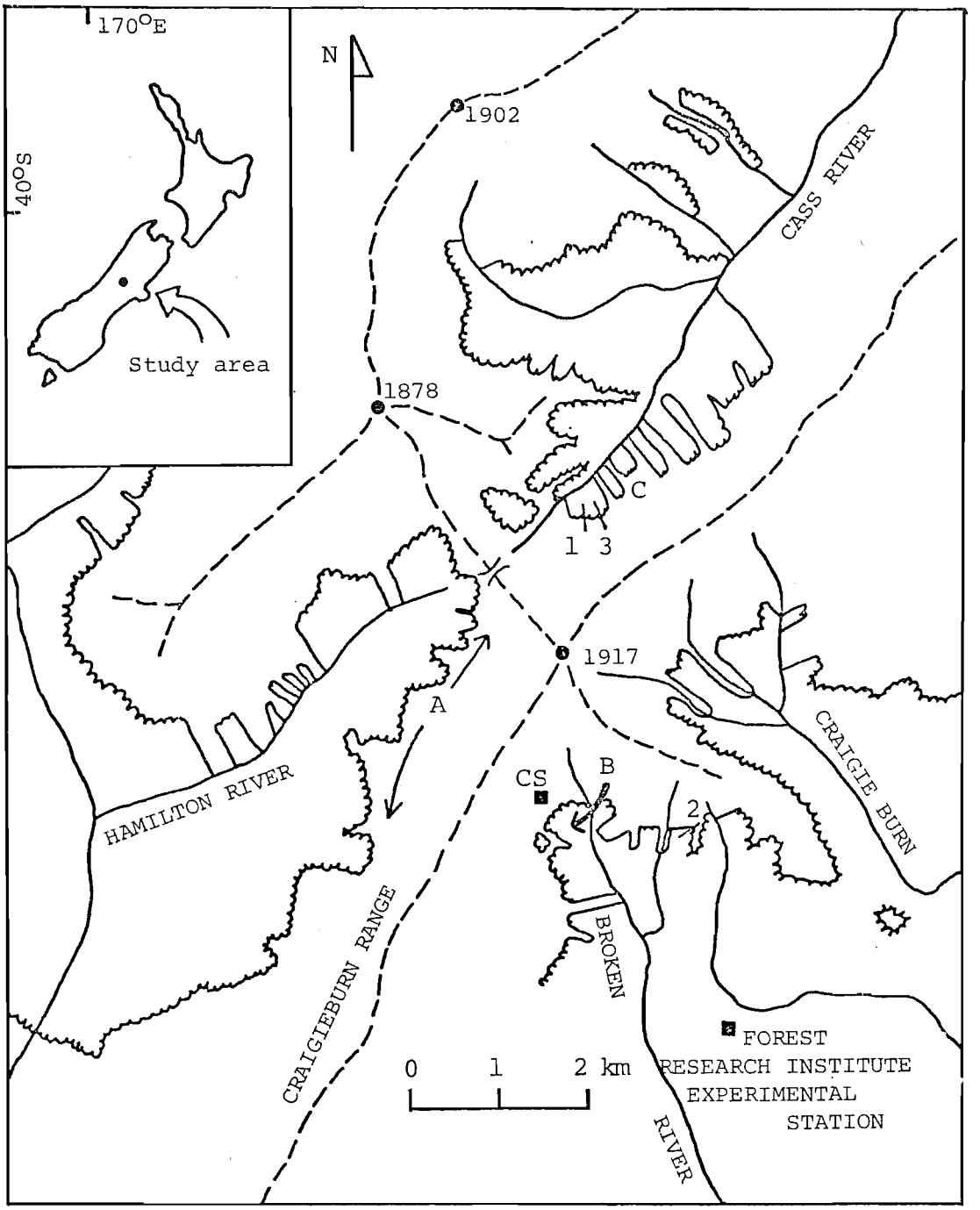


Figure A2.1 The study area. 1,2,3 - transects in Fig. A2.3. A, timberline depressed by fire. B, charcoal present under forest. C, charcoal present under grassland above depressed timberline. CS, climate station in Broken River Basin.

lower margin. The canopy is compact with a dense arrangement of many leaves and small twigs. These trees are of a multileader habit and layering, evidence of physical damage (broken stems) and winter desiccation and frost damage are common. This growth form is confined to the timberline margin (Fig. A2.4a) especially where snow lies to a depth of 1 m to 2 m late into spring. Sites are usually exposed to the wind and are often west-facing. P. Wardle (1963b, 1971, 1974) mentions similar forms.

A2.5.2 Tiered growth form (Fig. A2.2b)

In the tiered form (c.f. P.Wardle 1971) a wind deformed leader occurs above a section free of branches and leaves, in the zone of severest damage just above the winter snow pack. A compact canopy occurs close to the ground, under the winter snow pack. These plants occur at similar sites to the prostrate form.

A2.5.3 Cushion growth form (Fig. A2.2c)

The cushion growth form is compact and characterised by branches held close to the ground on the windward side. Most tree growth takes place on the leeward side. A distinctive feature is the abundant evidence of winter death in the form of dead foliage in spring. This uncommon growth form usually occurs on exposed spur crests at timberline. Similar forms occur at lower altitudes, on very exposed sites with shallow soils (J. Wardle 1970a, P. Wardle 1971, 1973b), but develop under different environmental conditions.

A2.5.4 Coppice growth form (Fig. A2.2d)

The main characteristics are a gnarled bole and multileader habit with branching in many directions. Trees of this form may have large diameter multileader stems up to 4 m tall or small diameter stems arising from large massive boles. This is the most common growth form in the timberline forests and occurs extensively downslope from prostrate growth forms (Fig. A2.4a) as well as at forest margins where snow does not drift to any great depth (e.g. spurs and rocky places). P. Wardle (1974) and Conway (1977) describe similar forms.

A2.5.5 Decurrent growth form (Fig. A2.2e)

The decurrent growth form is distinguished from the coppice form by the presence of long 'whippy' branches running downhill for several metres. Branches arise from the downhill side of the very large boles.

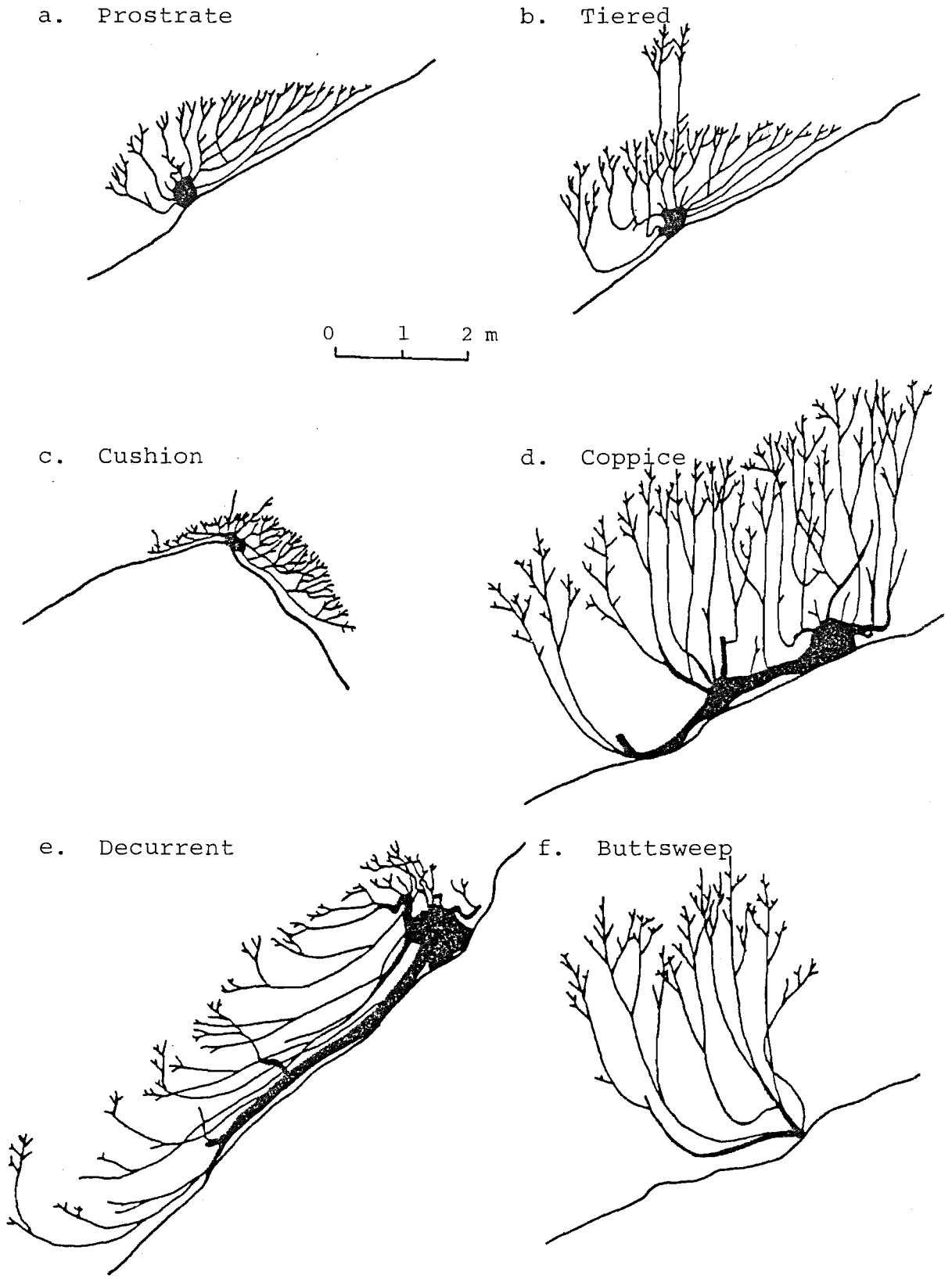


Figure A2.2 Line drawings of the six main *Nothofagus solandri* growth forms at the alpine timberline in the Craigieburn Range

These trees form open stands. This growth form occurs on steep slopes and is local in distribution, rarely forming timberline. Similar forms are mentioned by P. Wardle (1963b), J. Wardle and O'Loughlin (1964) and J. Wardle (1970c).

A2.5.6 Buttsweep growth form (Fig. A2.2f)

The buttsweep form typically lacks a gnarled bole but is characterised by a multileader habit and stems aligned approximately downhill, with a buttsweep of often more than one metre. The buttsweep growth form is found below timberline, usually just above tall erect forest (Fig. A2.4a and A2.4b) and is local in distribution.

A2.6 PROCESSES MODIFYING TREE GROWTH AT *NOTHOFAGUS SOLANDRI* TIMBERLINES

A2.6.1 Foliage death and shoot dieback

Dieback of shoot tips and death of foliage and buds commonly occurs in timberline *Nothofagus solandri* trees and is conspicuous in spring when the resultant orange-red foliage can be widespread. This dieback is confined to a narrow vertical canopy zone close to the winter snowpack surface. Foliage above and below this zone usually remains unaffected (e.g. in the tiered growth form). Dieback can be widespread amongst the forest margin trees; trees within the forest are rarely affected.

The premature death of foliage at timberline is mainly due to winter desiccation and frost damage. Winter desiccation is thought to occur through excessive transpiration from inadequately matured leaves exposed above the winter snow pack (Tranquillini 1979). The fine mycorrhizal roots of *Nothofagus solandri* trees are concentrated in the upper few centimetres of the soil and would require only shallow soil freezing to hinder water uptake. The effect of winter desiccation is most intense close to the snowpack surface where high radiation flux raises tissue temperatures, increasing transpiration rates. The snow pack often persists into late winter or early spring, when clear fine days commonly occur. Many *N.solandri* leaves observed at this time were noticeably orange around the margins, but remained green near the mid vein and main lateral veins. By early spring these leaves were completely orange. High wind speeds increasing cuticular transpiration and controlling snow deposition patterns could account for the wind-shaped appearance of some timberline trees.

Frost can cause widespread death of non-hardened tissues. Examination of stem sections indicated regular frost damage to spring wood with conspicuous distortion of vessels. Winter frost may also kill inadequately matured shoots (P. Wardle 1981). Blowing snow and ice close to the snowpack surface can cause mechanical damage to exposed shoots. Observed bark damage on exposed stems is probably due to such abrasion.

A2.6.2 Stem deformations

Stem deformation ranging from simple bending to severe contortions occur widely at timberline. They are caused by mechanical forces, primarily snow movement.

(i) Buttsweep

The simplest form of stem deformation is a buttsweep near the base of the stem, occurring in single and multiple leader trees. Typically all stems in the stand are aligned in a downhill direction (Fig. A2.2f). This modification occurs after disturbance by avalanche or windfall has opened up the forest. Subsequent regeneration is affected by snow movement tilting saplings. Both snow creep and avalanche can tilt saplings. Snow creep occurs when a light snow layer collapses under the weight of a heavier layer above with net downhill snow movement. Snow movement does not affect the more rigid older trees and uninterrupted vertical growth resumes with the buttsweep becoming fixed.

(ii) Prostrate stems

This is an extreme form of stem deformation with no vertical growth. Branching is in several directions, even uphill, thus excluding snow creep and avalanching as causes. Winter death of exposed shoots prevents vertical growth. Branches grow outwards close to the ground surface. The wind-shaped canopies of some timberline trees are in part attributable to this; branches are able to ascend higher on lee slopes where windspeed and the rate of transpiration are lower. At the forest margin (e.g. in the prostrate growth form) uphill growth also occurs in response to light.

(iii) Gnarled stems

Boles and stem bases are often gnarled and twisted, changing orientation in the vertical and horizontal planes. This modification usually occurs in combination with coppicing and is a result of breakage. The mechanical force of both snow avalanche and creep causes stem breakage, as also does severe icing of stems and accumulation of heavy wet snow in tree canopies. In winter, snow was observed to drift into the timberline margin prostrate growth forms, to a depth of 1 m to 2 m. Broken stems were conspicuous. After heavy snowfalls, broken twigs, branches and stems were frequently found on the forest floor, especially under coppice trees. The ability of *Nothofagus solandri* stems to heal after breakage is important in the formation of these gnarled stems and boles. The characteristic 'elbows' (Fig. A2.3) are examples of wound healing and occur after almost complete breakage of stems. When a shoot or stem is broken, the next order shoot can grow as the new leader in a direction often differing from that of the previous leader.

Trees of the decurrent growth form (Fig. A2.2e) illustrate the extreme form of this modification. Branches arising from the tops of the boles become severely gnarled and 'elbows' are common. Due to the open nature of these stands snow drifts into them to considerable depth. The steepness of the slope enhances downward snow movement. In one stand investigated (Fig. A2.4c), decurrent growth form trees up to 2 m tall were completely buried under winter snow.

A2.6.3 Coppicing

A distinctive feature of many timberline *Nothofagus solandri* trees is the presence of many stems arising from a single base. Coppicing through epicormic branching is a response to repeated death and breaking of stems and frequently occurs in *Nothofagus solandri* trees at the alpine timberline. The repeated occurrence of dieback and subsequent epicormic branching gives rise to the multileader habit common in many timberline trees. Epicormic branching is also influenced by light and gravity and is stimulated by sudden exposure to light (Kramer and Kozlowski 1979) (e.g. after the death of an adjacent tree). The tendency for multileader stems to be oriented away from each other

Figure A2.3 "Elbow" resulting from healing over of a severely damaged *Nothofagus solandri* stem

is also, presumably, a response to light. Bud release due to gravimorphism frequently occurs along the sides of avalanche tracks and similar processes may also occur in timberline trees.

Breakage of shoots and stems by mechanical forces (e.g. snow movement) is important in initiating coppicing. In some stands it is probable that large avalanches have sheared off stems previously present at the height of the frozen snowpack which protects the gnarled boles and subsequently epicormic branching has occurred. These forms all lack a single leader. The frequent occurrence of coppicing is an indicator of the frequent damage that occurs to timberline trees.

A2.6.4 Layering

Layering by adventitious rooting occurs in *Nothofagus solandri* trees at the alpine timberline (P. Wardle 1963b, J. Wardle 1970c), especially when a stem is partially buried in the ground because of downhill movement of talus or soil. Rooting can occur where a branch scar is present on the stem. In many of the timberline trees, especially the prostrate and coppice growth forms, branches running outwards from the tree bole produce adventitious roots. Commonly the connecting branch between the parent bole and the adventitiously rooted stem is rotten and in some cases the connecting branch is no longer present but scars on the parent bole and the adventitiously rooted stem remain.

In Switzerland, Kuoch and Amiet (1970) described isolated *Picea excelsa* groups in the timberline ecotone which have arisen through vegetative reproduction by layering. They consider that such regeneration is not possible in a closed stand because of dieback of lower branches. In *Nothofagus solandri* forests, however, layering does occur within the closed stand. Layering occurs in the prostrate and coppice growth forms and was also observed in the other forms to a lesser extent. However, layering is not as common in *N.solandri* trees as it is in many Northern Hemisphere gymnosperm species and was not observed to occur below the timberline ecotone.

A2.7 GENERAL DISCUSSION

A2.7.1 Sexual reproduction and vegetative proliferation

At the alpine timberline sexual reproduction is probably of much

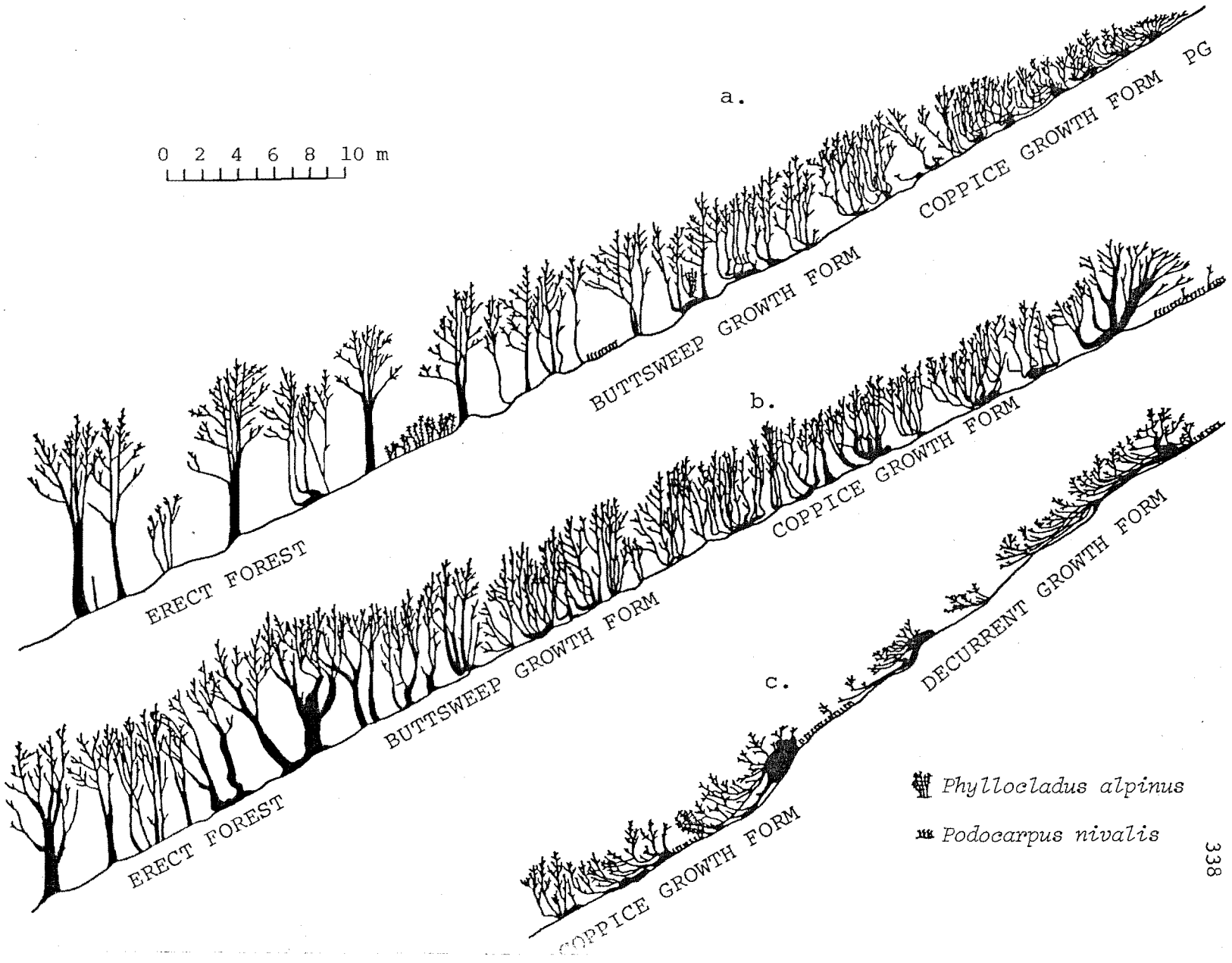
less importance to *Nothofagus solandri* trees than at lower altitudes. Good seed years in *N.solandri* forests occur irregularly and with increasing altitude the amount of seedfall and seed soundness declines (J. Wardle 1970c). Seed production at timberline (1350 m) was less than 5% of that at 1000 m. In the 1967 seed year, the soundness of the seedfall declined from 57% at 1000 m to 7% at timberline (1350 m). J. Wardle (1970c) found that the weight of seeds and germination percentages also declined with increasing altitude. Germination of sound seed fell from 20% at 1000 m to 5% at 1350 m. First year seedling death was also much higher at the alpine timberline.

It is likely that vegetative proliferation is important in allowing *Nothofagus solandri* trees to grow at the alpine timberline, especially during periods unfavourable to seedling growth. Both coppicing and layering occur and prolong the life of individual trees. Often the parent tree is dead but adventitiously rooted stems are present. It is therefore possible that several trees in a given area are genetically identical. The repeated dieback and subsequent epicormic branching from old boles also prolongs the life of the tree, at least at the base. *N.solandri* trees rarely exceed 300 years of age (P. Wardle 1963b, J. Wardle 1970d), although trees up to 380 years old were recognised during this study. However, it is probable that because of the processes described above, many of the large boles present may well be older. Unfortunately all the boles examined so far have been rotten, making their age difficult to establish. Vegetative proliferation is of little importance elsewhere in *N.solandri* forests (J. Wardle 1970c, 1970d) but is common in South American *Nothofagus* species, both at timberline and elsewhere (McQueen 1976). Although vegetative proliferation does occur in timberline *N.solandri* forests, it is less common than in many Northern Hemisphere gymnosperm forests.

A2.7.2 Spatial and temporal patterns

At the alpine timberline the growth forms present can differ over short distances and are dependent on site conditions. The relationship between the tree and factors affecting snow deposition and wind exposure are critical. Three main gradations affecting the the different growth forms present can be recognised.

Figure A2.4 Transects placed through *Nothofagus solandri* timberlines, Craigieburn Range. Refer to Fig. A2.1 for locations. a, Transect 1; timberline *N.solandri* forest illustrating the transition from erect trees to buttsweep trees, coppice trees and finally to prostrate trees (PG) at the forest margin. b, Transect 2; timberline *N.solandri* forest disturbed by fire and now lacking the typical timberline margin growth forms present in transect 1. c, Transect 3; timberline *N.solandri* forest illustrating the transition from coppice trees to decurrent trees with increasing altitude


a.
0 2 4 6 8 10 m
COPPICE GROWTH FORM PG
BUTTSWEEP GROWTH FORM
ERECT FOREST
b.
COPPICE GROWTH FORM
BUTTSWEEP GROWTH FORM
ERECT FOREST
c.
DECURRENT GROWTH FORM
COPPICE GROWTH FORM
Phyllocladus alpinus
Podocarpus nivalis

have developed at forest margins depressed by fire but in other instances this has not happened, possibly because of reduced snow deposition at lower altitudes. Fig. A2.4b shows a typical profile through a timberline forest whose margin has been removed by fire. The growth forms usually present at the forest margin are absent. Such open timberlines are quite common in the drier mountains of Canterbury and many of the apparently natural timberlines have in fact been modified by fire, descending from the alpine grasslands into the forest. Most European timberlines have also been modified by fire and other anthropogenic influences (Ellenberg 1966).

A2.7.4 Comparison with other *Nothofagus* timberlines

In southern South America, *Nothofagus* species often form timberline. The deciduous *N.pumilio* commonly occurs at timberline and is ecologically similar to *N.solandri* (McQueen 1976). At timberline *N.pumilio* is frequently stunted by snow influences (Veblen et al. 1977). A further species, *N.antarctica,* occurs above the erect *N.pumilio* timberline as krummholz. This deciduous species has genetically dwarfed races (McQueen 1976) and has no angiosperm equivalent in New Zealand, although the dwarf gymnosperm *Podocarpus nivalis* occurs in similar situations. Timberlines in Tasmania (Australia) are complex and strongly influenced by natural fire. Species of *Eucalyptus* and *Arthrotaxis* commonly occur at timberline; the dwarf deciduous *N.gunnii* occurs near timberline on exposed sites and is capable of surviving frequent snow and ice storms (Jackson 1973).

A2.8 CONCLUSIONS

The growth form modifications described here for *Nothofagus solandri* in the Craigieburn Range are more common among gymnosperm species at the alpine timberlines of the Northern Hemisphere. However, it would seem that similar environmental processes also affect angiosperm trees causing the formation of krummholz growth forms, although to a lesser extent. Snow and wind are thought to be particularly important. Many of the timberlines in the Craigieburn Range are depressed and have been influenced by past fires. In the area studied the timberline growth forms are confined to a narrow timberline ecotone at the upper forest margin, ecologically distinct from lower altitude *N.solandri* forests. Multileader tree habit and vegetative proliferation characterise this ecotone. The timberline ecotone in *N.solandri*

forests is narrow compared to those in Northern Hemisphere gymnosperm forests, but nevertheless the environment is severe enough to cause the presence of many deformed growth forms.

APPENDIX THREE

A COMPUTER PROGRAM TO FILTER TREE-RING CHRONOLOGIES*

A3.1 ABSTRACT

A computer program is presented that enhances variance at particular frequencies in tree-ring chronologies by the use of a digital filter. The program is written in FORTRAN-IV and runs on a Burroughs B6900 computer. It is designed to convert easily to any 32 bit computer with a FORTRAN-IV compiler. Notes on the use of the program and examples of output are given.

A3.2 INTRODUCTION

The computer program presented here is an aid to the study of climatic cycles and trends using tree-ring data. Tree-ring chronologies are developed from variable ring width series of climatically sensitive trees. Chronologies are produced by combining tree-ring measurements from several trees in which the pattern of ring width variation is similar and is closely related to growing season climate. Climate can influence tree growth on an annual basis (high frequency variation) or over long time periods (low frequency variation). The purpose of the program presented here is to enhance variation at a particular frequency while reducing that at other frequencies.

One method that has been used for studying cycles in time series data involves the removal of unwanted variance by the use of moving averages. In this approach, a smoothed series is derived from the original series by computing for each element a value which is the average of that element and some number of the following and preceding elements. The number of elements forward and back in the series from the target element which are involved in calculating the moving average is called the *extent* of the calculations. In this elementary approach to calculating a moving average, extent is the only factor the researcher can control to influence the outcome. The elements within

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* This computer program was developed with considerable assistance from George Gregg, then of the Computer Centre, University of Canterbury.

References cited in this Appendix are included in the main reference list of the thesis.

the extent are weighted equally (i.e. contribute equally to the derived value). The effect is to reduce the amplitude of all cycles in the original series except the longest. This tends to exaggerate long-term oscillations. Apparent cycles can be produced from entirely random series in this way (Mitchell et al. 1966). Equally weighted moving averages also tend to shift the phase of shorter cycles.

In a refinement of this approach, a different weight is chosen of each element that is involved in the calculation, depending on its distance from the target element. These weighted moving averages, known as digital filters, can minimise the undesirable side effects mentioned above. Careful selection of the extent of the calculations and of the weights applied can enable a researcher to study cycles or trends of whatever periodicity (i.e. wavelength) that is of most interest. Mutually exclusive filters have been applied to meteorological data to pass variation at a variety of different wavelengths (Craddock 1957). The weights used in a filter are chosen so as to reduce variance at particular frequencies, while enhancing that at other frequencies. Stockton and Fritts (1971) used two reciprocal digital filters to separate tree-ring chronology variance with a frequency of less than ten years (high pass filter) from variance with a frequency greater than ten years (low pass filter). In another study, a variety of digital filters were used in attempting to detect relationships between sunspot numbers and tree-ring widths (LaMarche and Fritts 1972). Fritts (1976) discusses in more detail the application and use of digital filters in tree-ring research.

The program presented here uses the weighted moving average method to filter tree-ring chronologies. The algorithm used is to compute for each element in the sequence a value that is a function of that element and the preceding and following few elements in the sequence, as in the following equation,

$$\bar{X}_t = \sum_{i=-n}^{i=+n} w_i \; x_{t+i}$$

where $\bar{X}$ is the weighted average corresponding to the t-th element and w_i is the weight by which the value of the element i units removed from t is multiplied. This result is stored as the corresponding element of a derived series. The extent of the calculations and the weights to be applied (i.e. the filter) are chosen by the user. By strongly and

positively weighting elements close to the central element and negatively weighting elements further from the central element, high frequency variations can be emphasised. However, increasing the length of the extent and positively weighting all elements has the effect of emphasising low frequency variations. The filter in the example used here is designed to separate variance with a wavelength greater than ten years from shorter duration variance (Stockton and Fritts 1971). The program is listed at the end of this appendix.

A3.3 USER GUIDE

A3.3.1 Control cards

Three control cards are needed to use the program. Examples of these cards are given below, and the derived sequence as printed by the program is presented in Fig. A3.1 and plotted in Fig. A3.2.

(i) TITLE CARD: Up to 80 characters.
e.g. MTB613 NOTHOFAGUS SOLANDRI CANTERBURY 14 TREES, 36 RADII

(ii) MAIN CONTROL CARD: All numbers right justified.

Columns 1-5; Number of values in original series (e.g. 200)
The current maximum is 1000.

Columns 6-10; Size of extent.
This is the number of weights on either side of the central value of the filter window (e.g. for a filter of size 13, the extent is 6.
See Fig. A3.1).

Column 15; Plot code.
1, original sequence only
2, derived sequence only
3, both (and is used in the example).

Columns 16-20; Number of times graph is to be plotted.
Current maximum is 19 and default is one copy.

(iii) FILTER CARDS: The filter values are listed in fields of eight columns (right justified), ten per card, for as many cards as necessary and include the decimal point. Up to 51 weights can be used. The weights used in the example are given at the top of Fig. A3.1.

MTB613 *NOTHOFAGUS SOLANDRI* CANTERBURY 14 TREES, 36RADII

LENGTH OF SEQUENCE = 220 EXTENT = 6

WEIGHTS are:

0.0003 0.0030 0.0161 0.0537 0.1208 0.1933 0.2256 0.1933 0.1208 0.0537

0.0161 0.0030 0.0003

DERIVED VALUES

1760	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.34251	1.38050	1.36886	1.32421
1770	1.27333	1.24908	1.27395	1.33785	1.40383	1.43888	1.43180	1.39233	1.32733	1.23694
1780	1.12616	1.01482	0.93124	0.89773	0.92138	0.98725	1.05686	1.08791	1.06629	1.01662
1790	0.97901	0.97529	0.98796	0.96556	0.86180	0.68615	0.51628	0.44701	0.51812	0.68856
1800	0.87266	1.00031	1.05040	1.03656	0.97643	0.88648	0.79768	0.75194	0.77424	0.85572
1810	0.96028	1.03909	1.04528	0.95343	0.78334	0.60473	0.49842	0.49607	0.55936	0.62544
1820	0.66626	0.69415	0.72277	0.74781	0.76469	0.77915	0.79671	0.81842	0.84196	0.84956
1830	0.80319	0.67601	0.48982	0.30717	0.18409	0.14094	0.17549	0.28534	0.46805	0.69937
1840	0.91720	1.04253	0.03827	0.95710	0.91425	0.99186	1.17053	1.35750	1.46526	1.46009
1850	1.36916	1.26224	1.20601	1.21152	1.23204	1.22303	1.19378	1.18920	1.22156	1.23291
1860	1.14263	0.93456	0.69643	0.55040	0.56530	0.71624	0.92653	1.12711	1.27904	1.35824
1870	1.34987	1.27120	1.18332	1.15304	1.19488	1.26552	1.31530	1.32223	1.27318	1.15118
1880	0.97334	0.81988	0.78414	0.88358	1.03645	1.13231	1.11852	1.02155	0.90280	0.81176
1890	0.77929	0.82404	0.93699	1.06995	1.16451	1.19521	1.17499	1.12740	1.06505	0.98585
1900	0.88088	0.75091	0.62097	0.53530	0.53001	0.60747	0.73893	0.88803	1.02468	1.12317
1910	1.16844	1.16806	1.14463	1.11734	1.09671	1.08817	1.09364	1.11165	1.13871	1.17297
1920	1.21574	1.26394	1.30390	1.32418	1.33186	1.34160	1.34752	1.32360	1.26058	1.18725
1930	1.14501	1.14580	1.15611	1.11944	1.00280	0.83405	0.69146	0.64299	0.69531	0.80022
1940	0.89840	0.95588	0.96901	0.94766	0.90213	0.84241	0.78436	0.75502	0.78012	0.85595
1950	0.94489	1.01086	1.05030	1.07991	1.10582	1.11558	1.09951	1.07208	1.06361	1.09062
1960	1.13828	1.17435	1.18030	1.16573	1.15043	1.13649	1.10325	1.03289	0.94634	0.90349
1970	0.94314	1.02514	1.05452	0.97027	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Figure A3.1 Example of information printed out by program FILTER. The weights used in the filter are listed at the top and the values for the derived sequence are listed below this.

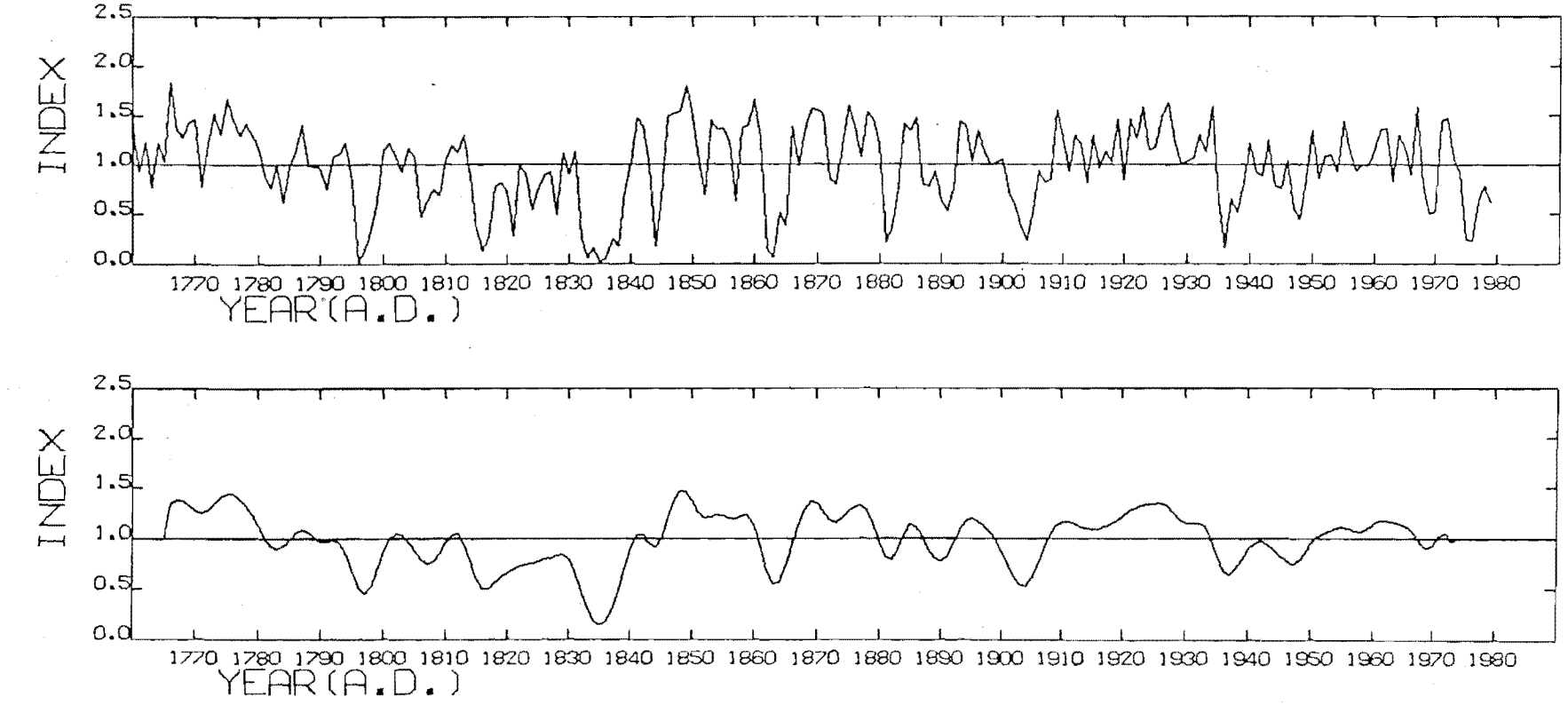


Figure A3.2 Example of plotted output from program FILTER. The original series is above the derived (filtered) series

A3.3.2 Data cards

Data cards have ten observations each in the format (7X, I4, 1X, 10I6). Each data card contains ten observations for a decade. The first year of the decade is given in columns 8-11 and the observations that follow include the decimal points and are right justified. For the decade starting 1770 in the example, the data card is set out as follows,

```
MTB613  1770  1.464  0.780  1.210  1.523  1.317  1.669  1.457  1.305
1.428  1.313
```

1770 is in columns 9-12. The first data card must always start with the first year of a decade (e.g. 1760), but the last data card can end on any year (e.g. 1981).

A3.3.3 Card order

The card order is as follows,

TITLE CARD
MAIN CONTROL CARD
FILTER CARDS (up to six cards)
DATA CARDS

A3.3.4 Error messages

The program checks the control card instructions and data and produces easily understood error messages (e.g. YOU HAVE ONLY 20 DATA CARDS AND THERE SHOULD BE 21). See program listing for other error messages.

A3.4 DISCUSSION

The printed output (Fig. A3.1) lists the title, length of sequence, extent, and the weights used in the filter. The values of the derived sequence are then listed in decadal groups. Plots of the derived and original sequences are shown in Fig. A3.2, with the original sequence above the derived sequence. As the filter uses 13 weights, the derived sequence is shorter by 12 years (6 at each end). The plots were produced on a Calcomp drum plotter coupled to the Burroughs B6900 computer at the Computer Centre, University of Canterbury.

Although developed on a Burroughs B6900 computer, the program was designed with the goal of being easily convertible to any 32 bit machine, including IBM, PRIME, and the Dec VAX. It is written in standard FORTRAN-IV and is well documented by use of liberal comments in the listing. The plotting commands will need alteration to run on other systems and have therefore been placed in a separate subroutine. To implement the program on another computer, it will be necessary to replace the plotting subroutine with a subroutine that will plot the arrays using the local plotting procedures. The program is listed at the end of this appendix.

```
C                    ******************
C                    * PROGRAM FILTER *
C                    ******************
C
C
C  DEVELOPED BY GEORGE GREGG (COMPUTER CENTRE) AND DAVID NORTON
C  (BOTANY DEPARTMENT), UNIVERSITY OF CANTERBURY, SEPTEMBER 1981
C
C  THIS PROGRAM WAS WRITTEN TO SMOOTH TREE-RING CHRONOLOGIES, BUT
C  CAN BE USED TO SMOOTH ANY TIME SERIES DATA.  THE ALGORITHM USED
C  IS TO COMPUTE FOR EACH ELEMENT IN THE SERIES A DERIVED VALUE THAT IS
C  A FUNCTION OF THAT ELEMENT AND THE PRECEEDING AND FOLLOWING FEW
C  ELEMENTS OF THE SERIES.  THIS WEIGHTED AVERAGE IS STORED AS THE
C  CORRESPONDING ELEMENT OF A DERIVED SEQUENCE.  THE ELEMENT BEING
C  COMPUTED IS THE CENTRE OF A WINDOW ON THE SEQUENCE.  THE SIZE OF
C  THE WINDOW AND THE WEIGHTS TO BE APPLIED TO EACH ELEMENT WITHIN
C  THE WINDOW CAN BE SET BY THE USER.    THE PROGRAM WILL OPTIONALLY
C  PLOT THE ORIGINAL SEQUENCE AND/OR THE DERIVED SEQUENCE.  THE USER
C  ALSO MAY SPECIFY THE NUMBER OF COPIES OF THE PLOT THAT ARE TO BE
C  PRODUCED.
C
C  THE PROGRAM WAS WRITTEN FOR THE BURROUGHS B6900, BUT HAS BEEN
C  DESIGNED TO BE EASY TO CONVERT TO ANY OTHER COMPUTER BY USING
C  STANDARD FORTRAN AND STORING CHARACTER DATA AT FOUR PER WORD.
C  VARIABLES AND ARRAYS ARE EXPLICITLY INITIALIZED TO ZERO IF REQUIRED.
C  THE PLOTTING CAPABILITY WILL BE DIFFERENT FOR EVERY COMPUTER, SO
C  THE PLOTTING HAS BEEN CODED IN A SEPARATE SUBROUTINE.  TO IMPLEMENT
C  THIS PROGRAM ON ANOTHER COMPUTER, IT WILL BE NECESSARY TO REPLACE
C  THE PLOTIT SUBROUTINE WITH A SUBROUTINE THAT WILL PLOT THE ARRAYS
C  USING THE LOCAL PLOTTING PROCEDURES.
C
C
C
C        ARRAYS
C        ------
      DIMENSION TITLE(20)
C
C     THIS ARRAY STORES A TITLE OF UP TO 80 CHARACTERS IN A4 FORMAT.
C
      DIMENSION SEQ(1000),WTMEAN(1000)
C
C     THESE TWO ARRAYS STORE THE ORIGINAL AND DERIVED SEQUENCES.  THE
C     MAX SIZE IS CURRENTLY 1000.  TO INCREASE THE LENGTH OF SEQUENCE
C     THAT CAN BE COMPUTED, CHANGE 1000 TO THE NUMBER REQUIRED IN THIS
C     DIMENSION STATEMENT AND IN THE IF(N.GT.1000) STATEMENT BELOW.
C     THE NEW LIMIT SHOULD BE A MULTIPLE OF 10, AND THE DIMENSION OF
C     IDATE SHOULD BE CHANGED TO ONE TENTH OF IT.
C
      DIMENSION IDATE(100)
C
C     THIS ARRAY IS FOR STORING THE DATE OF START OF DECADE FROM EACH
C     DATA CARD.  IT IS PURELY FOR DOCUMENTATION OF THE PRINTOUT FOR THE
C     BENEFIT OF THE USER, AND MAY BE OMITTED FROM THE DATA CARDS IF
C     THE USER WISHES.
C
      DIMENSION WEIGHT(51)
C
C     THIS ARRAY STORES THE WEIGHTS TO BE USED AS COEFFICIENTS IN
C     COMPUTING THE MOVING AVERAGE.  THE SIZE OF THE WINDOW IS ALWAYS
C     AN ODD NUMBER OF ELEMENTS WITH THE ELEMENT BEING COMPUTED AT
```

```
C     THE CENTRE.  THE USER SPECIFIES A PARAMETER CALLED THE EXTENT,
C     WHICH IS THE NUMBER OF ELEMENTS FORWARD AND BACK THAT ARE TO
C     PARTICIPATE IN THE COMPUTATION OF THE MOVING AVERAGE.  THE SIZE
C     OF THE WINDOW IS TWO TIMES THE EXTENT PLUS ONE.  THE CURRENT
C     WINDOW SIZE IS 51, ALLOWING AN EXTENT OF 25.  TO INCREASE THIS,
C     CHANGE 51 TO WHATEVER WINDOW SIZE IS REQUIRED ON THIS DIMENSION
C     STATEMENT, AND CHANGE THE IF(IXTENT.GT.25) STATEMENT BELOW.
C
      DIMENSION ALPHA(20)
C
C     THIS ARRAY IS USED TO READ A SURPLUS CARD, IF THERE IS ONE.
C
C
C
C         VARIABLES
C         ---------
C
C    N          THIS VARIABLE IS INPUT BY THE USER AND IS THE COUNT OF
C               ELEMENTS IN THE SERIES TO BE SMOOTHED.
C
C    IXTENT     THIS VARIABLE IS INPUT BY THE USER AND IS THE EXTENT OF
C               THE SEQUENCE TO BE INVOLVED IN CALCULATING THE MOVING
C               AVERAGE.
C
C    PLOTCD     THIS VARIABLE IS INPUT BY THE USER AND IS A CODE FOR
C               HOW TO DO THE PLOTTING, AS FOLLOWS:
C                    0 MEANS NO PLOT
C                    1 MEANS PLOT THE ORIGINAL SEQUENCE ONLY
C                    2 MEANS PLOT THE DERIVED SEQUENCE ONLY
C                    3 MEANS PLOT BOTH SEQUENCES.
C
C    NPLOT      THIS VARIABLE IS INPUT BY THE USER AND IS THE COUNT
C               OF THE NUMBER OF COPIES OF THE PLOT TO BE PRODUCED.
C
C    LIM        THIS VARIABLE IS COMPUTED IN THE PROGRAM AND IS THE
C               NUMBER OF DECADES IN THE SEQUENCE.
C
C    PFLAG      THIS VARIABLE IS USED IN THE PROGRAM TO "REMEMBER" IF
C               THERE HAVE BEEN NEGATIVE VALUES IN THE SEQUENCE .  IT
C               IS PASSED TO THE PLOTIT SUBROUTINE TO AID IN FORMATTING
C               THE PLOT.  VALUES ARE ZERO IF NO NEGATIVE VALUES OCCUR,
C               AND NEGATIVE IF ANY NEGATIVE VALUES DO OCCUR.
C
C
C
C   SET THE CARD READER AND PRINTER DESIGNATIONS
      RDR=5
      PRT=6
C   IF RUN ON A COMPUTER WHERE THE COMPILER DOES NOT USE 5 FOR READER
C   DESIGNATION AND 6 FOR PRINTER DESIGNATION, THESE SHOULD BE ALTERED
```

```
C        ****************
C        * MAIN PROGRAM *
C        ****************
C
C  READ THE TITLE CARD
C
      READ(RDR,900)TITLE
  900 FORMAT(20A4)
C
C  READ THE PARAMETER CARD AND CHECK FOR VALIDITY
C
      READ(RDR,901)N,IXTENT,PLOTCD,NPLOT
  901 FORMAT(4I5)
      IF(N.GT.1000)GO TO 810
      IF(IXTENT.GT.25)GO TO 820
C
C  READ THE WEIGHTS
C
      READ(RDR,902)(WEIGHT(I),I=1,(IXTENT*2+1))
  902 FORMAT(10F8.0)
C
C  WRITE THE PARAMETERS ON THE USER'S OUTPUT
C
      WRITE(PRT,903)TITLE,N,IXTENT,(WEIGHT(I),I=1,(IXTENT*2+1))
  903 FORMAT(1X,T25,20A4,///,'0',
     1     'LENGTH OF SEQUENCE=',I5,'    EXTENT=',I3,
     2//,1X,'WEIGHTS ARE:',(/,10F8.4))
C
C  CALCULATE HOW MANY DATA CARDS TO READ.  IF THE NUMBER OF ELEMENTS
C  IN THE SEQUENCE IS NOT AN EVEN MULTIPLE OF 10, AN EXTRA DATA CARD
C  WITH A PARTIAL DECADE MUST BE READ.
C
      LIM=N/10
      IF(LIM*10.NE.N)LIM=LIM+1
C
C  READ THE SEQUENCE.  IF END OF FILE OCCURS BEFORE READ IS COMPLETE,
C  GO TO LABEL 830, WHERE AN ERROR MESSAGE IS PRINTED AND PROGRAM STOPS.
C
      DO 5 I=1,LIM
           READ(RDR,904,END=830)IDATE(I),(SEQ(J),J=I*10-9,I*10)
  904      FORMAT(7X,I4,1X,10F6.0)
    5 CONTINUE
C
C  TRY TO READ ANOTHER CARD.  IF THERE IS ONE, USER HAS TOO MANY DATA
C  CARDS.  IF SO, GO TO LABEL 840, WHERE ERROR MESSAGE IS PRINTED.
C
      READ(RDR,905,END=10)ALPHA
  905 FORMAT(20A4)
      GO TO 840
   10 CONTINUE
C
C  INITIALIZE THE DERIVED SEQUENCE ARRAY TO ZERO, EXCEPT FOR THE FIRST
C  AND LAST FEW ELEMENTS.  A WEIGHTED AVERAGE CANNOT BE COMPUTED FOR
C  THESE BECAUSE THE EXTENT FALLS BEYOND THE RECORDED SEQUENCE, SO WE
C  INITIALIZE THESE TO 1 TO MAKE THE PLOT LOOK TIDIER.
C
      DO 80 I=1,N
           WTMEAN(I)=0
           IF(PLOTCD.EQ.0.)GO TO 80
           IF(I.LE.IXTENT.OR.I.GT.N-IXTENT) WTMEAN(I)=1.
```

```
   80 CONTINUE
      PFLAG=0
C
C  COMPUTE THE DERIVED SEQUENCE
C
      DO 90 I=IXTENT+1,N-IXTENT
           K=0
           DO 100 J=I-IXTENT,I+IXTENT
                K=K+1
                WTMEAN(I)=WTMEAN(I)+SEQ(J)*WEIGHT(K)
  100           CONTINUE
           IF(WTMEAN(I).LT.0)PFLAG=-1.5
   90 CONTINUE
C
C  WRITE OUT THE DERIVED VALUES
C
      WRITE(PRT,906)
  906 FORMAT('0',/,T40,'DERIVED VALUES',/,T40,'--------------')
      DO 120 I=1,LIM
      WRITE(PRT,907)IDATE(I),(WTMEAN(J),J=I*10-9,I*10)
  907 FORMAT(1X,I5,3X,10F10.5)
  120 CONTINUE
C
C  IF NO PLOT IS REQUESTED, PROGRAM IS FINISHED
C
      IF(PLOTCD.EQ.0) CALL EXIT
C
C  THE USER HAS REQUESTED PLOTTING.  FIRST CONFIRM THAT THE NUMBER
C  OF COPIES REQUESTED IS REASONABLE.  IF NOT, IT'S PROBABLY A
C  KEYPUNCH ERROR, SO GIVE USER A SINGLE PLOT AND A MESSAGE.
C
      IF(NPLOT.LT.20)GO TO 180
      WRITE(PRT,908)NPLOT
  908 FORMAT('0 TOO MANY PLOTS REQUESTED.  YOU HAVE ASKED FOR',I5,
     1' BUT ONLY ONE WILL BE PLOTTED.')
      NPLOT=1
C
C  CALL THE PLOTTING SUBROUTINE NPLOT TIMES
C
  180 DO 200 I=1,NPLOT
      CALL PLOTIT(PLOTCD,PFLAG,SEQ,WTMEAN,TITLE,IDATE,N,LIM)
  200 CONTINUE
      CALL EXIT
C
C
C
C
C
C        ******************
C        * ERROR ROUTINES *
C        ******************
C
  810 WRITE(PRT,500)
      WRITE(PRT,501)N
      CALL EXIT
  820 WRITE(PRT,500)
      WRITE(PRT,502)IXTENT
      CALL EXIT
  830 WRITE(PRT,500)
      WRITE(PRT,503)I-1,LIM
```

```
      CALL EXIT
  840 WRITE(PRT,500)
      WRITE(PRT,504)LIM,ALPHA
      CALL EXIT
  500 FORMAT('0AN INPUT ERROR HAS FORCED THE PROGRAM TO TERMINATE',
     1/,50('*'))
  501 FORMAT(' A SEQUENCE OF LENGTH',I5,' IS TOO LONG FOR THIS',
     1/,' VERSION OF THE PROGRAM.  IT CAN BE EASILY MODIFIED BY',
     2/,' A PROGRAMMER AND RECOMPILED TO EXTEND THE LIMIT')
  502 FORMAT(' AN EXTENT OF LENGTH',I5,' IS TOO LONG FOR THIS',
     1/,' VERSION OF THE PROGRAM.  IT CAN BE EASILY MODIFIED BY',
     2/,' A PROGRAMMER AND RECOMPILED TO EXTEND THE LIMIT')
  503 FORMAT('0YOU HAVE ONLY',I5,' DATA CARDS, AND THERE SHOULD BE',I5)
  504 FORMAT(' YOU HAVE TOO MANY DATA CARDS.',I5,' WERE EXPECTED,'
     1/,' BUT AFTER THAT MANY HAD BEEN READ, THE FOLLOWING CARD ',
     2'WAS ENCOUNTERED:',/,
     3'0',20A4)
      END
C
C
C
C
C
C                     ************************
C                     * PLOTTING SUBROUTINE *
C                     ************************
C
      SUBROUTINE PLOTIT(PLOTCD,PFLAG,SEQ,WTMEAN,TITLE,IDATE,N,LIM)
      DIMENSION XLAB(2),YLAB(1),FMT(1),X(2),Y(2)
      DIMENSION TITLE(20),ATITLE(14),SEQ(N),WTMEAN(N),IDATE(2)
      DATA XLAB/'YEAR(A.D.)'/,YLAB/'INDEX'/
      DATA FMT(1)/'F5.1'/,X/0,0/,Y/1,1/
C
C  SET UP FOR PLOTTING
C
      WRITE(ATITLE,130)TITLE
  130 FORMAT(20A4)
      WRITE(6,131)
  131 FORMAT('1')
      CALL AINIT(10*N+200)
      CALL AORIG(100,250)
      CALL ALAB(-100,575,ATITLE,78,2,2)
C
C  PLOT DERIVED SEQUENCE IF REQUESTED
C
      IF(PLOTCD.NE.2.AND.PLOTCD.NE.3) GO TO 140
      CALL ABOX(0,0,N/10+1,5,50,40,1)
      CALL ASCALE(-50,0,0,40,PFLAG,0.5,6,1,2,FMT,5)
      CALL ALINEX(0,5,WTMEAN,N-IWINDO,PFLAG,1.25)
      CALL ASCA(20,-20,50,0,IDATE(2),10,LIM,1,2)
      CALL ALAB(-55,70,YLAB,5,2,4)
      CALL ALAB(70,-45,XLAB,10,2,2)
      X(2)=N/10+1
      CALL ALINE(X,Y,2,0,0,2,1.25)
C
C  PLOT ORIGINAL SEQUENCE IF REQUESTED
C
  140 IF(PLOTCD.NE.1.AND.PLOTCD.NE.3) GO TO 160
      CALL AORIG(100,550)
      CALL ABOX(0,0,N/10+1,5,50,40,1)
```

```
      CALL ASCALE(-50,0,0,40,PFLAG,0.5,6,1,2,FMT,5)
      CALL ALINEX(0,5,SEQ,N,PFLAG,1.25)
      CALL ASCA(20,-20,50,0,IDATE(2),10,LIM,1,2)
      CALL ALAB(70,-45,XLAB,10,2,2)
      CALL ALAB(-55,70,YLAB,5,2,4)
      X(2)=N/10+1
      CALL ALINE(X,Y,2,0,0,2,1.25)
  160 CALL AEND
      RETURN
      END
```

APPENDIX FOUR

CHRONOLOGY LISTINGS

In this appendix the chronologies developed in this thesis are listed, plotted and their statistics presented. Site descriptions are given for all sites sampled, including those for which chronologies were not developed.

Site name *Aston Creek* Site code *AST*
Location *Craigieburn Range, Canterbury*
Latitude *43°08'S* Longitude *171°39'E*
Grid reference *NZMS1 S66 132044*
Species collected *Nothofagus solandri*
No. trees sampled *13* No. cores *26* No. discs *0*
Altitude *1300 m* Aspect *SW* Slope *35°*
Date of collection *15 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located on the western side of the Craigieburn Range in the Harper River catchment (Craigieburn Forest Park). Access is by foot from the University of Canterbury Cass Field Station, over Cass Saddle, to the NZ Forest Service Hamilton Hut (six hours), just upstream from the confluence of the Hamilton and Harper Rivers. The site is reached by following the prominent creek (not named on the map), immediately upvalley from the hut. Trees were sampled in an area of forest on the true right-hand side of this creek, just below timberline. The pure Nothofagus solandri forest, occurring on a moderate to steep slope, is open with a canopy at about 10 m. Accompanying vegetation is sparse and little N.solandri regeneration is present.

CHRONOLOGY STATISTICS

Chronology code	*AST630*	Interval (A.D.)	*1720-1979*
No. trees	*13*	No. radii	*26*
Mean ring width (mm)	*0.56*	% absent rings	*1.98*
Autocorrelation	*0.43*		
Mean sensitivity	*0.38*		
Mean standard error	*0.12*		

SAMPLE STATISTICS

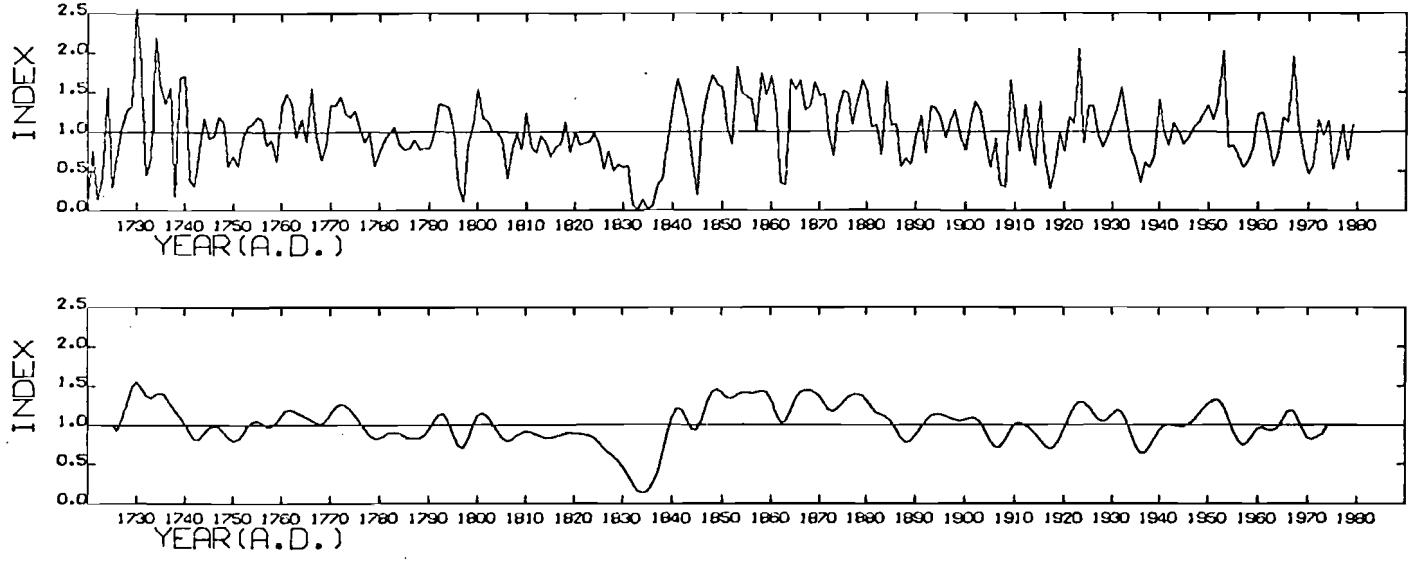
Interval analysed (A.D.) *1860-1979*
No. trees *10* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*33.04*
Differences between trees	*7.74*
Other	*59.22*

Cross-correlation analysis:

Radii within trees	*0.42*
Radii among trees	*0.34*
Between tree means	*0.35*

AST630 NOTHOFAGUS SOLANDRI CANTERBURY 13 TREES, 26 RADII



AST630 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1720	0.10	0.77	0.13	0.43	1.56	0.29	0.73	1.07	1.27	1.32
1730	2.56	1.85	0.44	0.66	2.20	1.58	1.35	1.56	0.17	1.67
1740	1.71	0.38	0.29	0.79	1.17	0.91	0.95	1.18	1.12	0.56
1750	0.69	0.56	0.93	1.06	1.09	1.19	1.14	0.82	0.89	0.62
1760	1.32	1.47	1.37	0.92	1.16	0.87	1.54	0.94	0.64	0.83
1770	1.33	1.33	1.43	1.22	1.17	1.25	1.03	0.85	0.99	0.56
1780	0.74	0.90	0.98	1.05	0.84	0.76	0.78	0.89	0.77	0.79
1790	0.78	0.98	1.34	1.33	1.30	1.01	0.31	0.09	0.86	1.09
1800	1.53	1.16	1.13	0.98	0.98	0.90	0.39	0.77	0.99	0.78
1810	1.23	0.79	0.73	0.95	0.86	0.67	0.81	0.84	1.12	0.73
1820	1.00	0.82	0.85	0.87	0.97	0.85	0.52	0.76	0.50	0.59
1830	0.53	0.57	0.06	0.00	0.14	0.02	0.05	0.31	0.39	0.90
1840	1.30	1.67	1.40	1.13	0.60	0.18	1.18	1.49	1.71	1.59
1850	1.55	1.06	0.83	1.83	1.48	1.45	1.40	1.00	1.74	1.45
1860	1.69	1.36	0.34	0.31	1.65	1.52	1.64	1.26	1.31	1.62
1870	1.45	1.48	0.96	0.69	1.30	1.51	1.47	1.09	1.39	1.65
1880	1.49	1.05	1.08	0.69	1.63	1.08	1.10	0.54	0.66	0.57
1890	0.92	1.19	0.72	1.31	1.30	1.16	0.91	1.12	1.28	0.93
1900	0.76	1.15	1.37	1.24	0.85	0.53	0.91	0.31	0.28	1.64
1910	1.14	0.74	1.34	0.86	0.56	1.37	0.64	0.25	0.55	0.98
1920	0.75	1.18	1.10	2.05	0.85	1.32	1.32	0.95	0.79	0.95
1930	1.12	1.28	1.56	1.16	0.79	0.61	0.35	0.61	0.54	0.71
1940	1.39	0.99	0.82	1.11	0.99	0.83	0.93	1.04	1.10	1.23
1950	1.34	1.15	1.37	2.02	0.80	0.83	0.69	0.54	0.61	0.78
1960	1.22	1.24	0.93	0.56	0.73	1.18	1.13	1.94	1.10	0.72
1970	0.46	0.58	1.15	0.94	1.13	0.52	0.74	1.10	0.64	1.09

The ring width index for each year was derived from 1 radius for the period 1720-1729; 2, 1730-1749; 5, 1750-1759; 10, 1760-1769; 12, 1770-1779; 15, 1780-1789; 18, 1790-1791; 19, 1792-1839; 24, 1840-1849; 25, 1850-1859; 26, 1860-1930; 23, 1931-1956; 22, 1957-1960; 21, 1961-1979.

SITE AND COLLECTION INFORMATION

Site name *Craigieburn Valley* Site code *CGB*
Location *Craigieburn Range, Canterbury*
Latitude *43°07'S* Longitude *171°42'E*
Grid reference *NZMS1 S66 184075*
Species collected *Nothofagus solandri*
No. trees sampled *12* No. cores *24* No. discs *0*
Altitude *1250 m* Aspect *NE* Slope *35°*
Date of collection *11 December 1980*
Collectors *D.A.Norton and A.E. Moore*

Site description:

This site is situated on the eastern side of the Craigieburn Range in Craigieburn Forest Park. Access is by road to the Craigieburn Valley Ski Club buildings adjacent to which are the sampled trees. From the Ski Club buildings, trees were sampled across a moderate slope towards an obvious avalanche track to the north. A dense understorey of Coprosma species is present and the ground ferns Polystichum vestitum and Blechnum penna-marina are common. The sampled Nothofagus solandri trees form part of the forest canopy at about 10 m to 12 m.

CHRONOLOGY STATISTICS

Chronology code	*CGB625*	Interval (A.D.)	*1740-1979*
No. trees	*12*	No. radii	*24*
Mean ring width (mm)	*1.22*	% absent rings	*1.43*
Autocorrelation	*0.45*		
Mean sensitivity	*0.37*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

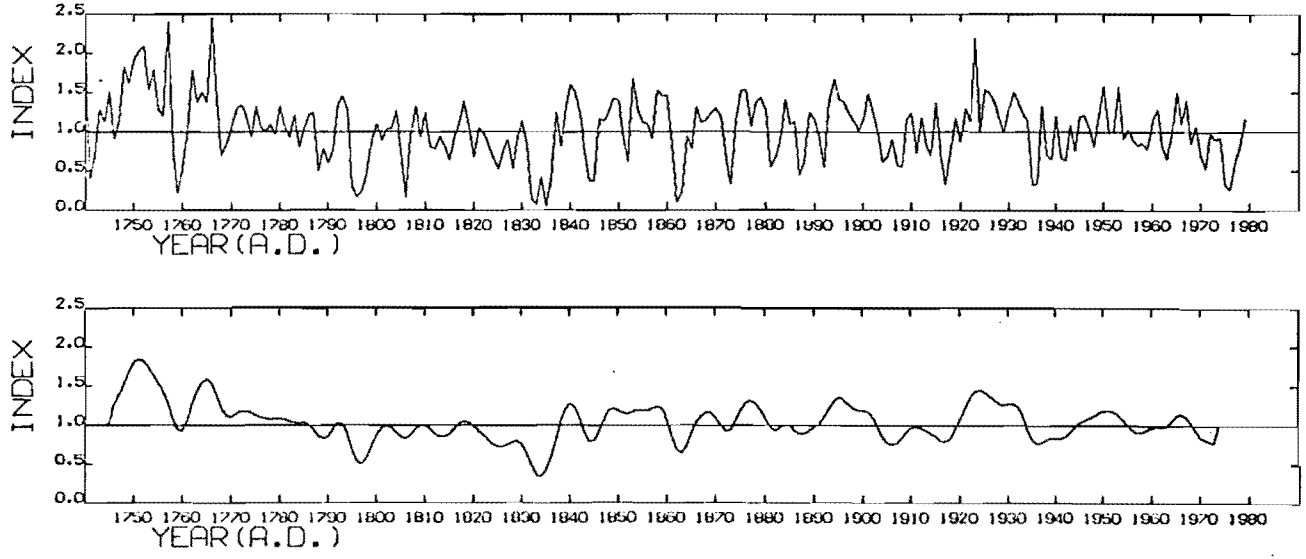
Interval analysed (A.D.) *1869-1979*
No. trees *9* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*44.49*
Differences between trees	*14.37*
Other	*41.14*

Cross-correlation analysis:

Radii within trees	*0.58*
Radii among trees	*0.46*
Between tree means	*0.47*

CGB625 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 24RADII



CGB625 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1740	1.88	0.39	0.68	1.29	1.12	1.51	0.91	1.13	1.82	1.61
1750	1.92	2.02	2.08	1.54	1.78	1.27	1.20	2.41	0.79	0.22
1760	0.51	1.03	1.78	1.36	1.51	1.37	2.46	1.39	0.70	0.83
1770	1.04	1.30	1.33	1.21	0.94	1.32	1.05	1.00	1.09	0.96
1780	1.32	1.05	0.92	1.21	0.79	1.03	1.21	1.25	0.50	0.78
1790	0.60	0.75	1.34	1.44	1.27	0.29	0.15	0.25	0.47	0.89
1800	1.09	0.88	1.04	1.04	1.25	0.74	0.16	0.93	1.34	0.92
1810	1.25	0.81	0.77	0.93	0.82	0.63	0.93	1.10	1.38	1.07
1820	0.67	1.04	0.98	0.83	0.66	0.52	0.75	0.89	0.52	0.93
1830	1.14	0.82	0.14	0.07	0.42	0.05	0.38	1.24	0.81	1.31
1840	1.59	1.50	1.22	0.73	0.37	0.37	1.16	1.14	1.25	1.42
1850	1.39	0.93	0.61	1.67	1.28	1.11	1.10	0.90	1.51	1.45
1860	1.46	0.82	0.10	0.21	0.93	0.78	1.30	1.11	1.15	1.24
1870	1.29	1.18	0.64	0.32	1.14	1.52	1.53	1.06	1.36	1.44
1880	1.27	0.55	0.65	0.85	1.40	1.08	1.13	0.44	0.61	1.24
1890	1.16	0.91	0.54	1.40	1.67	1.41	1.38	1.24	1.13	1.01
1900	1.16	1.49	1.24	0.97	0.61	0.67	0.91	0.56	0.55	1.16
1910	1.23	0.73	1.18	0.80	0.69	1.36	0.71	0.32	0.71	1.18
1920	0.86	1.30	1.12	2.18	1.00	1.53	1.49	1.37	1.17	0.99
1930	1.30	1.50	1.37	1.23	1.12	0.32	0.34	1.32	0.70	0.64
1940	1.20	0.66	0.62	1.08	0.75	1.20	1.21	1.03	0.81	1.21
1950	1.56	0.98	1.01	1.57	0.91	1.03	0.88	0.82	0.84	0.77
1960	1.15	1.28	0.82	0.64	0.95	1.50	1.09	1.39	0.85	1.07
1970	0.70	0.52	0.98	0.89	0.92	0.32	0.26	0.61	0.82	1.16

The ring width index for each year was derived from 1 radius for the period 1740-1759; 4, 1760-1769; 6, 1770-1779; 8, 1780-1789; 9, 1790-1799; 12, 1800-1809; 14, 1810-1819; 17, 1820-1839; 21, 1840-1869; 22, 1870-1879; 24, 1880-1968; 23, 1969-1978; 22, 1979.

Site name *Camp Stream* Site code *CMP*
Location *Craigieburn Range, Canterbury*
Latitude *43°08'S* Longitude *171°42'E*
Grid reference *NZMS1 S66 177053*
Species collected *Nothofagus solandri*
No. trees sampled *19* No. cores *35* No. discs *3*
Altitude *1350 m* Aspect *SE* Slope *30°*
Date of collection *11 December 1980*
Collectors *D.A.Norton, A.E. Moore and W.Schönenberger*

Site description:

Camp Stream (unofficial name) is situated in the upper Broken River catchment on the eastern side of the Craigieburn Range within the Craigieburn Forest Park. Access is via the Broken River Ski Field road from the Forest Park Headquarters, for about three kilometres, and then up a formed road on the north side to timberline.

The site is about five minutes walk west from the road end. Cored trees were located immediately below the timberline ecotone in an area of tall (8-10 m) monotypic Nothofagus solandri forest. The trees are of a single leader growth form and little N.solandri regeneration or other species are present. Drainage is moderate to good.

CHRONOLOGY STATISTICS

Chronology code	*CMP614*	Interval (A.D.)	*1759-1979*
No. trees	*16*	No. radii	*35*
Mean ring width (mm)	*0.79*	% absent rings	*0.50*
Autocorrelation	*0.47*		
Mean sensitivity	*0.31*		
Mean standard error	*0.07*		

SAMPLE STATISTICS

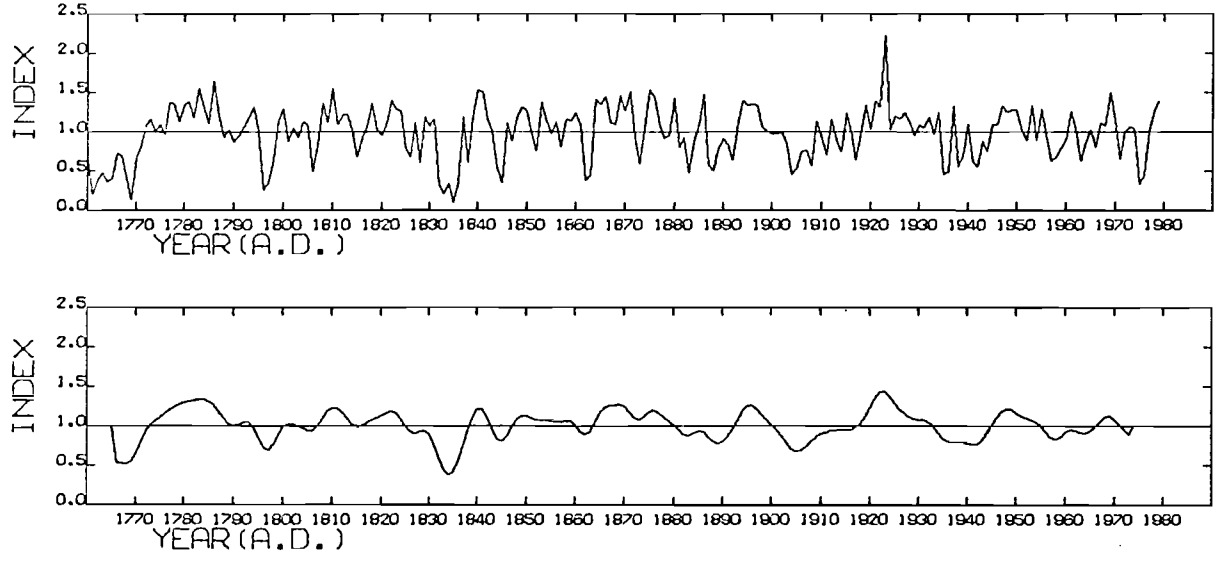
Interval analysed (A.D.) *1869-1979*
No. trees *14* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*39.73*
Differences between trees	*11.87*
Other	*48.40*

Cross-correlation analysis:

Radii within trees	*0.54*
Radii among trees	*0.42*
Between tree means	*0.42*

CMP614 NOTHOFAGUS SOLANDRI CANTERBURY 16 TREES, 35RADII



CMP614 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1759										0.67
1760	0.65	0.18	0.36	0.47	0.35	0.40	0.72	0.69	0.41	0.12
1770	0.67	0.83	1.09	1.16	1.00	1.09	0.95	1.37	1.35	1.12
1780	1.34	1.38	1.18	1.56	1.30	1.10	1.65	1.21	0.92	1.02
1790	0.85	0.94	1.05	1.17	1.30	1.00	0.25	0.35	0.64	1.13
1800	1.30	0.87	1.04	0.92	1.12	1.09	0.48	0.82	1.37	1.10
1810	1.54	1.09	1.21	1.22	1.02	0.66	0.92	1.07	1.35	1.02
1820	0.94	1.10	1.39	1.28	1.26	0.78	0.67	1.11	0.59	1.18
1830	1.07	1.15	0.30	0.19	0.33	0.08	0.35	1.18	0.59	1.17
1840	1.52	1.51	1.16	0.99	0.54	0.34	1.11	0.87	1.18	1.31
1850	1.25	0.97	0.75	1.37	1.13	0.97	1.12	0.80	1.16	1.13
1860	1.23	1.08	0.38	0.43	1.41	1.34	1.45	1.11	1.09	1.46
1870	1.26	1.51	0.93	0.59	1.01	1.53	1.43	1.09	0.91	0.96
1880	1.42	0.79	0.91	0.48	0.87	1.08	1.47	0.58	0.49	0.79
1890	0.91	0.83	0.63	1.10	1.39	1.33	1.34	1.34	1.05	1.01
1900	0.98	0.97	0.99	0.85	0.44	0.52	0.75	0.76	0.56	1.13
1910	0.93	0.70	1.16	0.89	0.74	1.23	1.00	0.63	0.97	1.33
1920	1.02	1.38	1.31	2.22	1.02	1.19	1.16	1.24	1.13	0.94
1930	1.09	1.05	1.18	0.96	1.25	0.45	0.48	1.32	0.54	0.69
1940	1.09	0.61	0.55	0.88	0.75	1.08	1.09	1.32	1.24	1.27
1950	1.26	1.01	0.88	1.34	0.88	1.28	0.95	0.62	0.67	0.78
1960	0.90	1.26	1.03	0.62	0.85	1.03	0.79	1.11	1.08	1.49
1970	1.15	0.65	0.99	1.05	1.04	0.33	0.45	1.00	1.27	1.38

The ring width index for each year was derived from 1 radius for 1759; 2 for the period 1760-1763; 3, 1764; 5, 1765-1774; 6, 1775-1776; 8, 1777-1778; 9, 1779; 12, 1780-1783; 13, 1784-1785; 15, 1786; 17, 1787-1789; 21, 1790-1791; 22, 1792-1793; 23, 1794-1798; 24, 1799-1804; 25, 1805-1808; 26, 1809; 27, 1810-1819; 28, 1820-1826; 29, 1827-1839; 33, 1840-1843; 34, 1844-1868; 35, 1869-1915; 34, 1919-1979.

Site name *Cream Creek* Site code *CRC*
Location *Cropp River, Westland*
Latitude *43°05'S* Longitude *170°59'E*
Grid reference *NZMS1 S64 537115*
Species collected *Libocedrus bidwillii*
No. trees sampled *106* No. cores *182* No. discs *3*
Altitude *800 m* Aspect *N* Slope *5-45°*
Date of collection *January 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located in the Cropp River catchment, a tributary of the Whitcombe and Hokitika Rivers. Access was by helicopter; foot access from the Hokitika River road end (35 km south of Hokitika township) takes two days. The site is approximately 1.5 km downstream from the NZ Forest Service Cropp River hut and is located on the true right-hand side of the river. The stand is below Reckless Torrent and approximately opposite a prominent (ultramafic) rockbluff on the true left. Cream Creek (unofficial name) is an inconspicuous stream where it joins the Cropp River, but forms a long vegetated slip in its upper reaches and bounds the west (upstream) side of the stand.

The forest consists of Archeria traversii, Dracophyllum traversii, Myrsine divaricata and Olearia ilicifolia forming a low canopy at 3-4 m. Griselinia littoralis is abundant in the subcanopy. The cored Libocedrus bidwillii trees are scattered through the forest and grow as emergents above the main canopy. A dense ground cover of shrubs, tree seedlings, herbs, ferns and bryophytes is present.

CHRONOLOGY STATISTICS

Chronology code	*CRC601*	Interval (A.D.)	*1460-1978*
No. trees	*15*	No. radii	*25*
Mean ring width (mm)	*0.67*	% absent rings	*0.21*
Autocorrelation	*0.71*		
Mean sensitivity	*0.13*		
Mean standard error	*0.16*		

SAMPLE STATISTICS

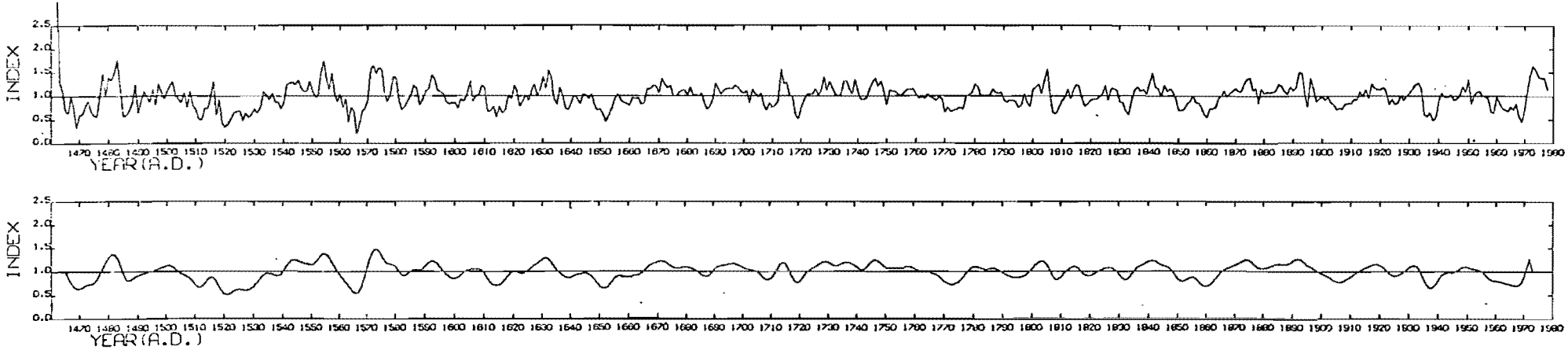
Interval analysed (A.D.) *1849-1978*
No. trees *10* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*27.06*
Differences between trees	*32.92*
Other	*40.02*

Cross-correlation analysis:

Radii within trees	*0.58*
Radii among trees	*0.29*
Between tree means	*0.30*

CRC601 LIBOCEDRUS BIDWILLII WESTLAND 15 TREES, 25 RADII



CRC601 LIBOCEDRUS BIDWILLII WESTLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1460	3.58	3.04	3.52	1.30	1.13	0.69	0.63	1.01	0.74	0.33
1470	0.60	0.61	0.80	0.89	0.69	0.59	0.56	0.99	1.48	1.00
1480	1.39	1.32	1.48	1.75	1.15	0.56	0.58	0.68	0.85	1.24
1490	0.64	0.91	1.09	0.97	0.85	1.14	0.79	1.26	1.10	0.94
1500	1.09	1.22	1.29	0.99	0.93	0.84	1.07	0.74	1.10	0.79
1510	0.71	0.51	0.47	0.74	0.72	0.95	1.29	0.60	0.92	0.40
1520	0.34	0.38	0.53	0.63	0.66	0.68	0.47	0.64	0.53	0.58
1530	0.72	0.63	0.74	1.09	1.00	0.91	1.05	0.85	0.87	0.72
1540	0.85	1.23	1.26	1.29	1.23	1.34	1.16	1.10	1.08	1.31
1550	1.12	0.97	0.97	1.49	1.73	1.36	1.14	1.48	1.02	0.88
1560	1.03	0.74	0.94	0.44	0.75	0.67	0.19	0.39	0.67	0.73
1570	0.89	1.54	1.64	1.47	1.59	1.56	1.04	0.87	1.05	1.39
1580	1.39	0.89	0.70	0.76	0.89	1.01	1.22	1.16	0.80	0.92
1590	1.09	1.13	1.43	1.36	1.10	1.08	1.04	0.86	0.82	0.85
1600	0.85	0.72	0.94	0.87	1.04	1.32	0.87	1.00	1.03	1.22
1610	1.16	0.65	0.67	0.77	0.55	0.77	0.61	0.68	1.01	0.93
1620	1.22	1.09	0.77	0.89	1.00	0.89	1.11	1.25	1.01	1.13
1630	1.41	1.14	1.55	1.37	0.95	0.80	1.17	1.01	0.73	0.70
1640	0.84	1.02	0.93	0.81	1.03	1.00	0.93	1.04	0.80	0.68
1650	0.73	0.61	0.44	0.59	0.75	0.93	1.03	0.91	0.85	0.83
1660	0.79	0.96	0.93	0.95	0.81	0.85	1.15	1.14	1.21	1.20
1670	1.04	1.37	1.23	1.16	1.21	0.99	0.97	1.06	1.11	1.13
1680	1.01	1.19	0.99	1.03	0.98	1.05	0.84	0.71	0.78	0.94
1690	1.27	1.14	1.04	1.12	1.14	1.16	1.14	1.22	1.17	1.08
1700	1.05	1.10	0.84	1.14	1.05	0.97	1.06	0.80	0.69	0.85
1710	0.75	0.80	0.89	1.57	1.26	1.29	1.01	0.97	0.59	0.51
1720	0.74	0.90	1.03	1.03	1.03	1.14	1.01	1.11	1.40	1.11
1730	1.31	1.15	1.03	0.99	1.03	1.31	1.32	1.14	1.03	1.34
1740	1.10	0.92	0.91	0.96	1.14	1.29	1.37	1.19	1.31	1.10
1750	0.81	1.12	1.10	1.08	1.02	0.99	1.08	1.13	1.14	1.14
1760	1.02	0.94	0.99	0.94	1.04	0.97	0.95	0.90	0.97	0.94
1770	0.65	0.76	0.66	0.69	0.71	0.76	0.71	0.96	1.02	1.05
1780	1.24	1.20	1.00	1.01	1.00	1.00	1.14	1.07	1.04	1.08
1790	0.91	0.85	0.91	0.89	0.88	0.75	0.79	1.04	0.86	0.76
1800	1.13	1.20	1.24	1.04	1.33	1.57	1.00	0.63	0.62	0.74
1810	0.89	0.97	1.15	0.94	1.13	1.23	1.19	0.94	0.77	0.83
1820	0.91	0.93	0.92	0.97	1.04	1.23	0.90	1.15	1.13	1.10
1830	0.85	0.86	0.67	0.60	0.90	1.12	1.19	1.09	1.13	1.02
1840	1.25	1.48	1.17	1.14	0.97	1.22	1.09	1.14	1.07	0.93
1850	0.69	0.69	0.72	0.83	0.87	1.00	0.84	0.85	0.74	0.60
1860	0.53	0.72	0.71	0.75	0.95	1.00	1.11	0.98	1.06	1.11
1870	1.16	1.09	1.09	1.25	1.35	1.38	1.11	1.18	0.83	1.14
1880	1.05	1.09	1.06	1.08	1.09	1.25	1.20	1.10	1.03	1.20
1890	1.11	1.18	1.49	1.48	1.03	0.76	1.38	1.18	0.87	0.93
1900	0.98	0.90	0.97	0.86	0.81	0.71	0.73	0.72	0.82	0.84
1910	0.84	0.93	0.91	1.10	0.99	1.14	0.95	1.26	1.16	1.14
1920	1.13	1.18	1.06	0.81	0.93	0.83	0.85	1.02	0.90	1.00
1930	1.06	1.13	1.23	1.27	1.16	0.61	0.56	0.65	0.47	0.54
1940	0.90	1.06	0.98	0.96	1.02	0.90	0.93	1.01	1.19	1.07
1950	1.34	0.83	1.01	1.09	1.10	0.99	0.99	0.93	0.67	0.63
1960	0.98	0.85	0.73	0.71	0.67	0.77	0.71	0.83	0.58	0.44
1970	0.73	1.10	1.44	1.63	1.55	1.39	1.37	1.39	1.12	

The ring width index for each year was derived from 1 radius for the period 1460-1462; 2, 1463-1578; 3, 1579-1603; 4, 1604-1608; 5, 1609-1625; 6, 1626-1665; 8, 1666-1683; 9, 1684-1698; 10, 1699-1701; 11, 1702-1712; 12, 1713-1717; 13, 1718-1724; 14, 1725-1728; 16, 1729-1733; 17, 1734-1744; 18, 1745-1749; 19, 1750-1757; 20, 1758-1768; 21, 1769-1791; 22, 1792-1802; 23, 1803-1832; 24, 1833-1848; 25, 1849-1978.

SITE AND COLLECTION INFORMATION

Site name *Doubtful Creek* Site code *DBT*
Location *Craigieburn Range, Canterbury*
Latitude *43°06'S* Longitude *171°37'E*
Grid reference *NZMS1 S66 111098*
Species collected *Nothofagus solandri*
No. trees sampled *13* No. cores *26* No. discs *0*
Altitude *1400 m* Aspect *NE* Slope *30°*
Date of collection *17 December 1980*
Collectors *D.A.Norton and A.E. Moore*

Site description:

This site is located on the south side of the Black Range in the upper Harper River catchment (Craigieburn Forest Park). Access is from State Highway 73 at Cass, via Cass Saddle and Hamilton Hut, or at Bealey, via Lagoon Saddle. The site is a full days walk from the road. Doubtful Creek is followed from its confluence with the Harper River until a steep (the first) avalanche track on the true left-hand side is reached. A stiff climb up through the forest immediately upstream from this, gains timberline. Trees were cored immediately below timberline in an area of mixed multi-leader and single-leader Nothofagus solandri trees up to 8 m tall; only single leader trees were cored. The scrub layer includes Podocarpus nivalis, Gaultheria depressa and various Coprosma species. The site is well drained with a deep (30 cm) soil.

CHRONOLOGY STATISTICS

Chronology code	*DBT629*	Interval (A.D.)	*1780-1979*
No. trees	*13*	No. radii	*26*
Mean ring width (mm)	*1.03*	% absent rings	*1.23*
Autocorrelation	*0.46*		
Mean sensitivity	*0.35*		
Mean standard error	*0.08*		

SAMPLE STATISTICS

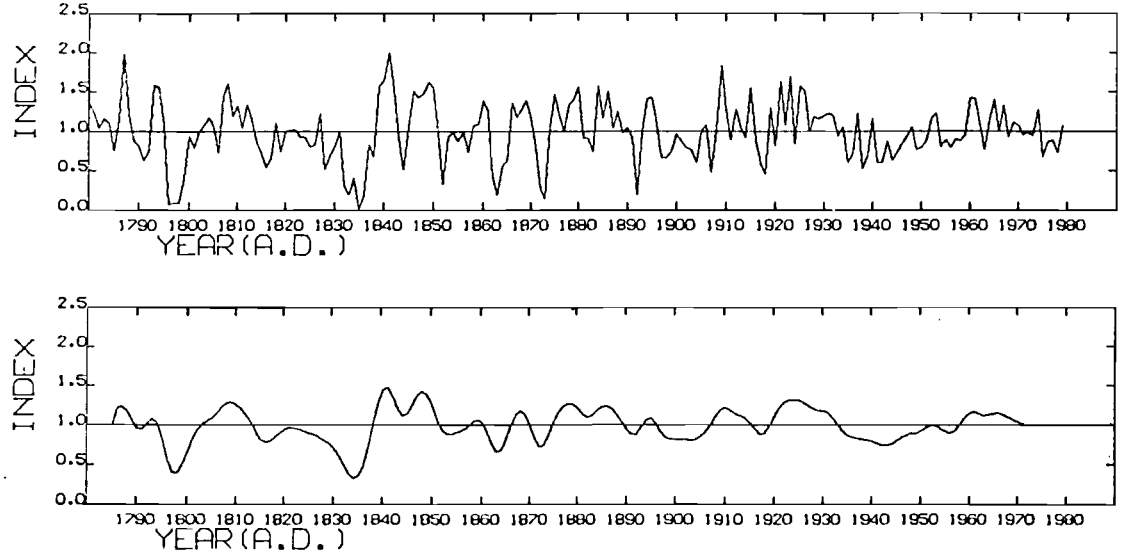
Interval analysed (A.D.) *1880-1979*
No. trees *11* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*43.46*
Differences between trees	*17.29*
Other	*39.25*

Cross-correlation analysis:

Radii within trees	*0.65*
Radii among trees	*0.46*
Between tree means	*0.47*

DBT629 NOTHOFAGUS SOLANDRI CANTERBURY 13 TREES, 26 RADII



DBT629 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1780	1.35	1.24	1.04	1.16	1.09	0.74	1.14	1.99	1.21	0.86
1790	0.81	0.62	0.75	1.58	1.56	1.09	0.05	0.08	0.09	0.39
1800	0.93	0.78	1.00	1.07	1.17	1.05	0.72	1.44	1.61	1.18
1810	1.32	1.03	1.34	1.14	0.86	0.71	0.53	0.66	1.11	0.74
1820	1.00	1.00	1.02	0.91	0.92	0.79	0.82	1.22	0.51	0.68
1830	0.79	1.00	0.29	0.19	0.41	0.01	0.17	0.83	0.67	1.57
1840	1.65	2.00	1.54	0.92	0.51	1.04	1.50	1.42	1.48	1.62
1850	1.54	0.98	0.32	0.92	0.98	0.87	0.98	0.73	1.07	1.09
1860	1.38	1.24	0.42	0.18	0.56	0.62	1.36	1.17	1.27	1.38
1870	1.16	0.78	0.26	0.13	1.05	1.47	1.19	0.99	1.34	1.40
1880	1.55	0.90	0.90	0.73	1.57	1.15	1.51	1.04	1.25	0.97
1890	1.04	0.90	0.19	0.98	1.41	1.42	1.08	0.66	0.66	0.74
1900	0.96	0.87	0.78	0.76	0.60	1.00	1.07	0.47	1.02	1.84
1910	1.26	0.88	1.27	1.04	0.91	1.54	0.88	0.58	0.45	1.30
1920	0.81	1.63	1.07	1.70	0.83	1.57	1.51	0.98	1.18	1.15
1930	1.20	1.22	1.20	0.93	1.05	0.59	0.71	1.22	0.52	0.69
1940	1.15	0.59	0.60	0.87	0.62	0.71	0.84	0.94	1.04	0.76
1950	0.78	0.87	1.15	1.21	0.79	0.88	0.78	0.90	0.87	0.94
1960	1.42	1.41	1.08	0.76	1.14	1.40	1.00	1.32	0.92	1.11
1970	1.07	0.95	0.98	0.93	1.27	0.67	0.86	0.88	0.72	1.07

The ring width index for each year was derived from 1 radius for the period 1780-1789; 2, 1790-1799; 6, 1800-1809; 9, 1810-1819; 11, 1820-1829; 12, 1830-1839; 16, 1840-1849; 19, 1850-1859; 20, 1860-1879; 24, 1880-1889; 26, 1890-1979.

SITE AND COLLECTION INFORMATION

Site name *Entwood* Site code *ENT*
Location *Craigieburn Range, Canterbury*
Latitude *43°06'S* Longitude *171°41'E*
Grid reference *NZMS1 S66 164094*
Species collected *Nothofagus solandri*
No. trees sampled *12* No. cores *23* No. discs *0*
Altitude *1250 m* Aspect *NE* Slope *5°*
Date of collection *23 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Entwood (unofficial name) is located in the upper Cass Valley, Craigieburn Forest Park, about three hours walk from the University of Canterbury Field Station at Cass. From the NZ Forest Service Cass Valley hut, a two minute walk reaches the forest edge and open tussock basins leading up to Cass Saddle. 300 to 500 m to the west, a large isloated stand of forest occurs. The sampled trees are located at the lowest (north east) corner of this stand. Tall, 12 m to 16 m, Nothofagus solandri trees were sampled across a hummocky moranic area. Drainage appears to be good on the hummocks where the trees grow, but deep soils in the hollows appear to be less well drained. Associated shrub species include Podocarpus nivalis and Coprosma c.f. pseudocuneata.

CHRONOLOGY STATISTICS

Chronology code	*ENT615*	Interval (A.D.)	*1744-1979*
No. trees	*12*	No. radii	*23*
Mean ring width (mm)	*1.01*	% absent rings	*1.96*
Autocorrelation	*0.54*		
Mean sensitivity	*0.38*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

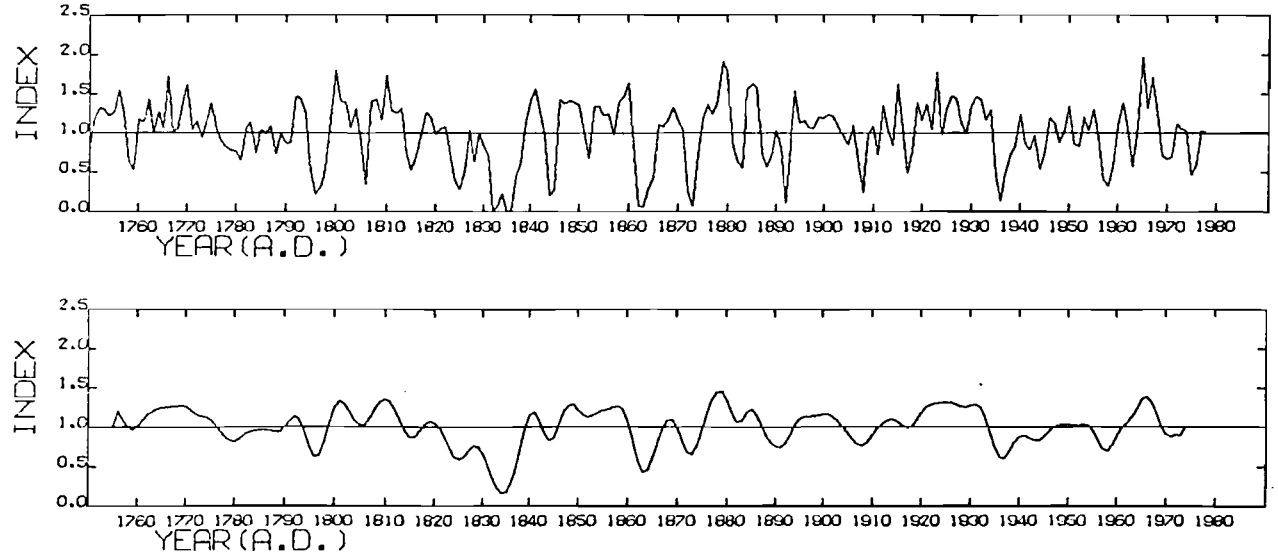
Interval analysed (A.D.) *1850-1965*
No. trees *10* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*50.34*
Differences between trees	*19.89*
Other	*29.77*

Cross-correlation analysis:

Radii within trees	*0.73*
Radii among trees	*0.56*
Between tree means	*0.57*

ENT615 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 23RADII



ENT615 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1744					0.72	1.02	0.82	0.88	0.97	0.69
1750	0.83	1.18	1.31	1.29	1.21	1.26	1.55	1.25	0.64	0.52
1760	1.17	1.13	1.42	0.99	1.27	1.06	1.72	1.01	1.05	1.38
1770	1.61	1.03	1.14	0.93	1.15	1.38	1.04	0.88	0.81	0.76
1780	0.76	0.64	1.04	1.13	0.73	1.03	0.99	1.09	0.72	0.98
1790	0.86	0.87	1.46	1.43	1.25	0.51	0.20	0.30	0.53	1.17
1800	1.80	1.40	1.39	1.05	1.31	0.88	0.34	1.41	1.42	1.15
1810	1.73	1.27	1.24	1.31	0.75	0.52	0.70	0.98	1.25	1.20
1820	0.97	1.06	1.07	0.74	0.38	0.27	0.51	1.03	0.62	1.00
1830	0.82	0.71	0.01	0.06	0.22	0.00	0.00	0.44	0.62	1.14
1840	1.41	1.56	1.26	0.97	0.20	0.27	1.42	1.37	1.41	1.38
1850	1.35	1.02	0.67	1.33	1.34	1.22	1.23	0.97	1.38	1.44
1860	1.63	0.86	0.06	0.04	0.27	0.42	1.11	1.07	1.15	1.32
1870	1.16	1.02	0.25	0.06	0.72	1.18	1.35	1.23	1.41	1.91
1880	1.77	0.89	0.62	0.55	1.56	1.62	1.57	0.73	0.56	0.71
1890	1.04	0.81	0.09	0.84	1.53	1.12	1.14	1.06	1.05	1.19
1900	1.18	1.24	1.20	1.07	0.96	0.84	1.10	0.66	0.23	0.98
1910	1.08	0.73	1.35	1.03	0.83	1.62	1.07	0.48	0.77	1.39
1920	1.16	1.37	1.03	1.77	0.97	1.29	1.46	1.43	1.11	0.99
1930	1.34	1.45	1.42	1.14	1.29	0.47	0.12	0.47	0.70	0.83
1940	1.23	0.85	0.77	0.95	0.53	0.73	1.18	1.12	0.88	1.01
1950	1.33	0.85	0.82	1.20	1.02	1.29	0.94	0.39	0.32	0.56
1960	1.09	1.39	1.06	0.57	1.06	1.96	1.31	1.71	1.24	0.71
1970	0.66	0.69	1.11	1.05	1.02	0.46	0.58	1.03	0.99	0.99

The ring width index for each year was derived from 1 radius for the period 1744-1745; 2, 1746; 3, 1747-1748; 4, 1749-1752; 5, 1753-1754; 6, 1755-1758; 7, 1759-1764; 8, 1765; 9, 1766-1789; 10, 1790-1799; 11, 1800-1836; 12, 1837; 13, 1838-1839; 20, 1840-1849; 21, 1850-1876; 22, 1877-1894; 23, 1895-1965; 22, 1966-1979.

SITE AND COLLECTION INFORMATION

Site name *Ghost Creek* Site code *GHC*
Location *Broken River Basin, Canterbury*
Latitude *43°15'S* Longitude *171°45'E*
Grid reference *NZMS1 S66 222917*
Species collected *Nothofagus solandri*
No. trees sampled *17* No. cores *26* No. discs *1*
Altitude *870 m* Aspect *NW* Slope *20 -40°*
Date of collection *28 July 1981*
Collectors *P.F.Aston and D.A.Norton*

Site description:

This site is located on the north side of the Torlesse Range on the property of Castle Hill sheep station. Access is via State Highway 73 to the Porter River, 45 km north of Springfield. The Porter River is followed downstream for about one km to Ghost Creek. Five trees were sampled on a terrace edge on the true left-hand side of the river, and the remaining trees grow on bluffs and steep talus slopes on the true right-hand side of the river. Associated species in the rather open Nothofagus solandri forest include Coprosma linarifolia, Cyathodes juniperina, Corokia cotoneaster and Griselinia littoralis. All the sampled trees grow on well drained substrates.

CHRONOLOGY STATISTICS

Chronology code	*GHC607*	Interval (A.D.)	*1795-1980*
No. trees	*12*	No. radii	*20*
Mean ring width (mm)	*1.41*	% absent rings	*0.23*
Autocorrelation	*0.44*		
Mean sensitivity	*0.32*		
Mean standard error	*0.08*		

SAMPLE STATISTICS

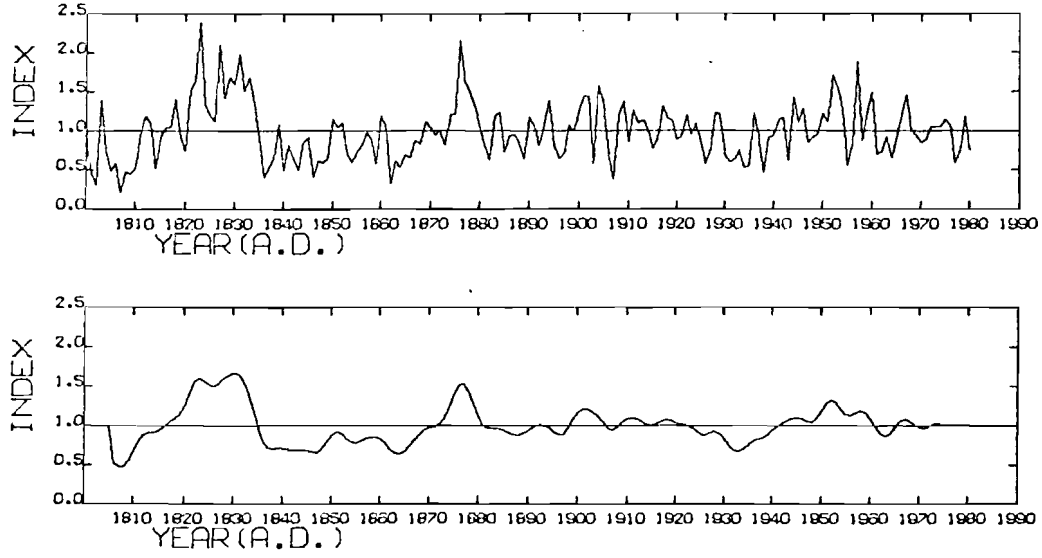
Interval analysed (A.D.) *1890-1978*
No. trees *8* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*27.24*
Differences between trees	*29.31*
Other	*43.45*

Cross-correlation analysis:

Radii within trees	*0.59*
Radii among trees	*0.29*
Between tree means	*0.31*

GHC607 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 20RADII



GHC607 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1795						0.88	1.34	0.33	0.44	1.22
1800	0.90	0.44	0.30	1.39	0.74	0.48	0.58	0.20	0.47	0.44
1810	0.50	0.94	1.19	1.08	0.51	0.92	1.03	1.04	1.39	0.90
1820	0.74	1.53	1.64	2.39	1.33	1.18	1.11	2.09	1.39	1.68
1830	1.58	1.98	1.49	1.68	1.34	0.91	0.40	0.52	0.64	1.07
1840	0.49	0.81	0.63	0.49	0.85	0.91	0.40	0.61	0.58	0.64
1850	1.15	1.04	1.10	0.69	0.59	0.73	0.81	0.97	0.87	0.57
1860	1.19	1.07	0.31	0.61	0.53	0.69	0.65	0.87	0.82	1.11
1870	1.03	0.94	1.00	0.81	1.19	1.20	2.15	1.64	1.48	1.29
1880	1.05	0.81	0.62	1.18	1.23	0.72	0.92	0.94	0.82	0.63
1890	1.17	1.05	0.80	1.08	1.38	0.80	0.63	0.69	1.07	0.98
1900	1.25	1.44	1.44	0.57	1.57	1.32	0.69	0.37	1.18	1.37
1910	0.84	1.26	1.09	1.14	0.98	0.76	0.91	1.30	1.15	1.12
1920	0.88	0.92	1.19	0.95	1.09	0.88	0.57	0.76	1.22	1.20
1930	0.69	0.59	0.62	0.75	0.52	0.53	1.22	0.94	0.46	0.91
1940	0.93	1.12	1.17	0.61	1.42	1.10	1.29	0.85	0.91	0.65
1950	1.22	1.11	1.71	1.53	1.27	0.56	0.82	1.88	0.87	1.25
1960	1.48	0.69	0.73	0.92	0.65	0.88	1.19	1.46	1.00	0.93
1970	0.85	0.89	1.04	1.05	1.05	1.13	1.07	0.58	0.73	1.18
1980	0.75									

The ring width index for each year was derived from 1 radius for the period 1795-1838; 2, 1839-1848; 3, 1849-1853; 4, 1854-1865; 5, 1866-1867; 6, 1868-1872; 7, 1873-1874; 10, 1875-1876; 11, 1877-1881; 12, 1882; 13, 1878-1879; 14, 1880; 15, 1881-1884; 16, 1885; 17, 1886-1890; 18, 1891; 19, 1892-1894; 20, 1895-1906; 21, 1907-1971; 19, 1972-1978; 17, 1979; 16, 1980.

SITE AND COLLECTION INFORMATION

Site name *Hidden Creek* Site code *HDC*
Location *Craigieburn Range, Canterbury*
Latitude *43°08'S* Longitude *171°36'E*
Grid reference *NZMS1 S66 086043*
Species collected *Nothofagus solandri*
No. trees sampled *12* No. cores *21* No. discs *0*
Altitude *1350 m* Aspect *W* Slope *30°*
Date of collection *16 December 1980*
Collectors *D.A.Norton and A.E. Moore*

Site description:

Hidden Creek is located on the south side of the Grey Range (Craigieburn Forest Park) and drains into the Harper River 4 km below the Hamilton Creek junction. Access is on foot from the University of Canterbury Cass Field Station via Cass Saddle and Hamilton hut; about one and a half days walk. Hidden Creek is followed until it goes underground below rock avalanche debris not far from the forest margin. Once this is reached, the forest margin is followed north up to the ridge on the true left-hand side of Hidden Creek. Nothofagus solandri trees were sampled in floristically poor 8-10 m tall forest stand immediately below the ridge on its western (Hidden Creek) side.

CHRONOLOGY STATISTICS

Chronology code	*HDC632*	Interval (A.D.)	*1730-1979*
No. trees	*12*	No. radii	*21*
Mean ring width (mm)	*0.58*	% absent rings	*1.37*
Autocorrelation	*0.49*		
Mean sensitivity	*0.34*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

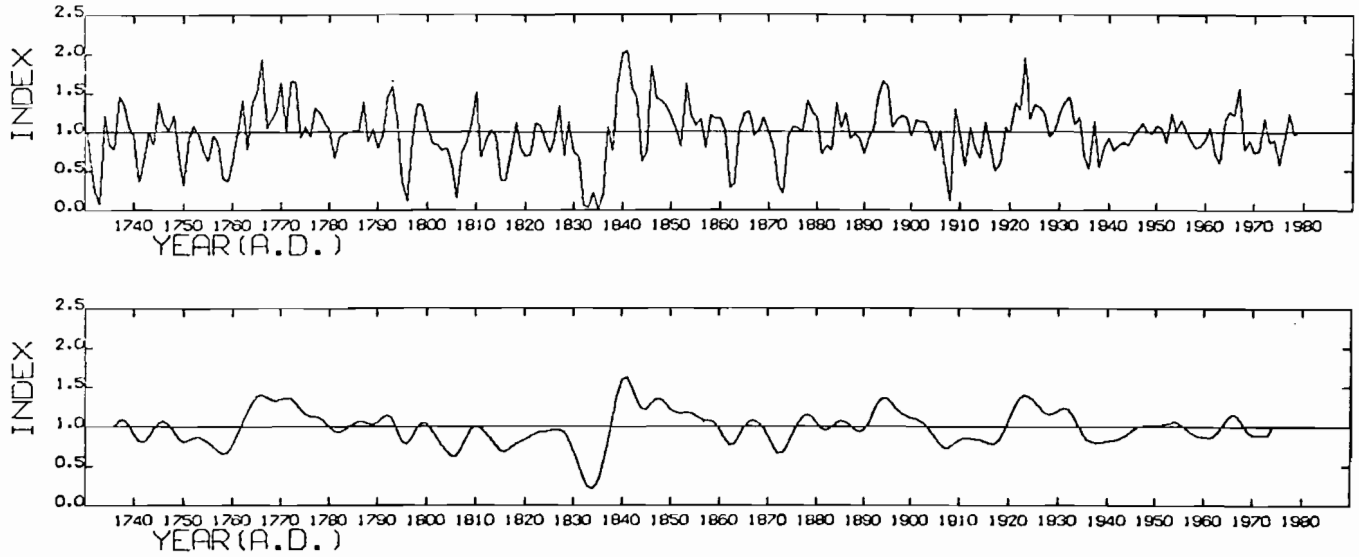
Interval analysed (A.D.) *1850-1979*
No. trees *8* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*38.50*
Differences between trees	*19.98*
Other	*41.52*

Cross-correlation analysis:

Radii within trees	*0.58*
Radii among trees	*0.41*
Between tree means	*0.42*

HDC632 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 21 RADII



HDC632 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1730	1.31	0.68	0.23	0.07	1.20	0.83	0.76	1.45	1.33	1.05
1740	0.96	0.36	0.64	1.00	0.83	1.38	1.09	1.03	1.21	0.70
1750	0.30	0.92	1.08	0.97	0.76	0.62	0.96	0.86	0.40	0.36
1760	0.64	0.99	1.41	0.77	1.38	1.50	1.94	1.04	1.16	1.27
1770	1.63	1.00	1.64	1.63	0.92	1.07	0.93	1.31	1.23	1.11
1780	1.02	0.66	0.92	0.98	0.98	1.01	1.00	1.39	0.87	1.05
1790	0.79	0.96	1.44	1.59	1.09	0.35	0.11	0.90	1.34	1.34
1800	1.04	0.85	0.83	0.76	0.80	0.57	0.15	0.72	0.86	1.09
1810	1.51	0.67	0.89	1.02	0.93	0.37	0.37	0.74	1.12	0.79
1820	0.68	0.70	1.11	1.09	0.89	0.74	0.93	1.34	0.70	1.12
1830	0.74	0.68	0.06	0.02	0.22	0.00	0.20	1.06	0.76	1.59
1840	2.01	2.03	1.56	1.43	0.62	0.73	1.85	1.42	1.40	1.33
1850	1.20	1.03	0.81	1.61	1.21	1.06	1.16	0.79	1.20	1.15
1860	1.17	1.01	0.27	0.34	1.04	1.23	1.26	0.94	1.00	1.19
1870	0.99	0.80	0.32	0.21	0.92	1.06	1.05	1.00	1.40	1.24
1880	1.18	0.71	0.81	0.76	1.37	1.05	1.25	0.90	0.97	0.91
1890	0.73	0.93	1.05	1.46	1.65	1.58	1.06	1.16	1.21	1.19
1900	0.94	1.15	1.13	1.12	0.98	0.76	1.02	0.52	0.10	1.30
1910	0.97	0.56	1.06	0.79	0.66	1.12	0.80	0.49	0.60	1.06
1920	0.99	1.36	1.28	1.94	1.16	1.34	1.31	1.23	0.94	1.00
1930	1.24	1.37	1.45	1.09	1.18	0.69	0.51	1.14	0.55	0.81
1940	0.92	0.76	0.82	0.87	0.82	0.94	1.02	1.11	1.00	0.97
1950	1.07	1.04	0.86	1.24	1.01	1.14	1.02	0.91	0.79	0.60
1960	0.89	1.05	0.72	0.59	1.15	1.25	1.20	1.55	0.78	0.89
1970	0.74	0.74	1.17	0.85	0.89	0.58	0.89	1.24	0.96	1.00

The ring width index for each year was derived from 1 radius for the period 1730-1739; 3, 1740-1749; 4, 1750-1779; 7, 1780-1789; 9, 1790-1809; 13, 1810-1836; 14, 1837-1839; 18, 1840-1849; 19, 1850-1909; 20, 1910-1919; 21, 1920-1979.

SITE AND COLLECTION INFORMATION

Site name *Kea Flat* Site code *KEA*
Location *Landsborough Valley, South Westland*
Latitude *43°52'S* Longitude *169°47'E*
Grid reference *NZMS1 S88 485153*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *19* No. discs *5*
Altitude *1150 m* Aspect *NW* Slope *10-20°*
Date of collection *10, 11, 13 February 1982*
Collectors *D.A.Norton and R.K.Harper*

Site description:

Foot access to the Kea Flat sampling site is not easy, taking at least three days from the Haast Pass road. Helicopter access was used here. The site is located at timberline on the true left- of the Landsborough River above Kea Flat. The site is on a spur between Kea Stream and McKerrow Creek. Trees were sampled a short distance below timberline in pure Nothofagus menziesii forest with a canopy at between 8 and 10 m. Soils are largely organic. The shrub layer is dominated by several species including Myrsine divaricata, Pseudopanax simplex, Archeria traversii, Coprosma species and Dracophyllum traversii. Many trees are gnarled and sampling was confined to trees with a straight bole.

CHRONOLOGY STATISTICS

Chronology code	*KEA637*	Interval (A.D.)	*1580-1980*
No. trees	*8*	No. radii	*15*
Mean ring width (mm)	*0.93*	% absent rings	*0.74*
Autocorrelation	*0.18*		
Mean sensitivity	*0.37*		
Mean standard error	*0.13*		

SAMPLE STATISTICS

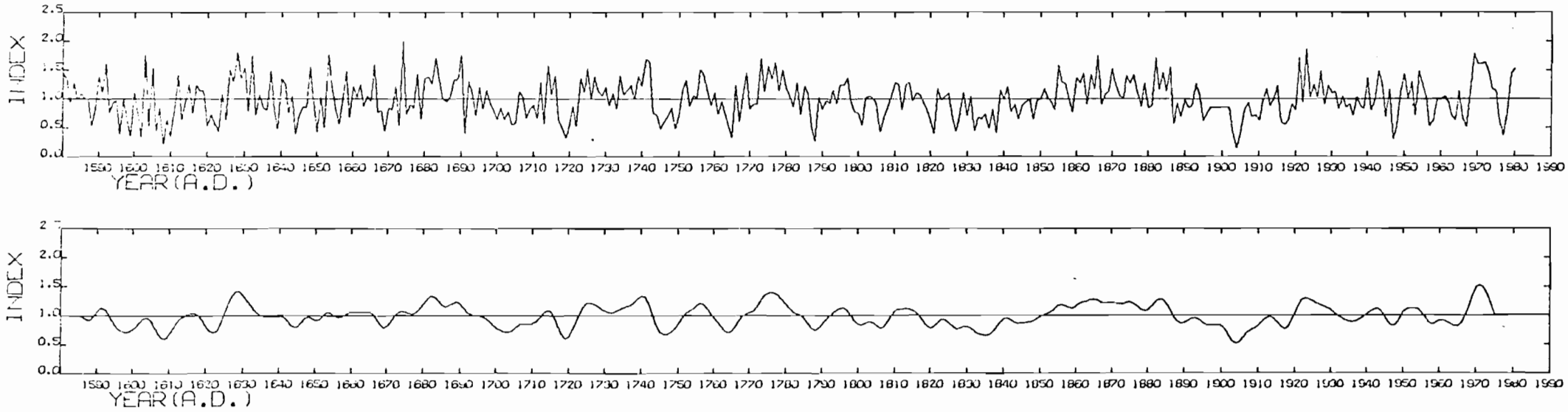
Interval analysed (A.D.) *1881-1980*
No. trees *5* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*28.43*
Differences between trees	*24.32*
Other	*47.25*

Cross-correlation analysis:

Radii within trees	*0.56*
Radii among trees	*0.30*
Between tree means	*0.33*

KEA637 NOTHOFAGUS MENZIESII SOUTH WESTLAND 8 TREES, 15 RADII



KEA637 NOTHOFAGUS MENZIESII SOUTH WESTLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1580	1.42	1.36	0.93	1.27	0.97	1.09	1.00	0.99	0.53	0.84
1590	1.38	1.10	1.60	0.76	0.92	0.98	0.38	0.98	0.64	0.36
1600	1.10	0.77	0.33	1.75	0.52	1.53	0.45	0.83	0.21	0.65
1610	0.35	0.80	1.41	0.63	0.95	1.26	0.75	1.23	1.13	1.13
1620	0.53	0.73	0.56	0.43	1.08	0.63	1.50	1.29	1.81	1.34
1630	1.56	0.79	1.74	0.72	1.07	0.84	0.80	1.49	0.80	0.48
1640	1.35	1.25	0.74	1.05	0.38	0.70	0.86	0.84	1.55	0.94
1650	0.42	1.06	0.50	1.76	1.21	0.85	0.55	0.93	1.47	0.67
1660	1.21	1.02	1.23	0.87	1.04	0.96	1.58	0.76	0.80	0.43
1670	0.84	0.80	1.23	0.53	1.99	0.72	0.90	0.84	1.41	0.65
1680	1.34	1.37	1.25	1.71	1.31	1.00	0.95	1.05	1.33	1.32
1690	1.76	0.39	1.29	1.08	0.70	1.20	0.82	1.14	0.93	0.80
1700	0.64	0.84	0.64	0.79	0.54	0.56	1.12	1.03	0.66	0.83
1710	0.89	0.66	1.29	0.55	1.57	1.08	1.40	0.65	0.48	0.32
1720	0.52	0.87	0.52	1.35	1.11	1.52	0.99	1.38	1.10	1.04
1730	1.20	0.89	1.10	0.82	1.39	1.07	1.15	1.23	0.97	1.39
1740	1.23	1.69	1.64	0.75	0.71	0.48	0.61	0.69	0.85	0.48
1750	0.71	1.14	1.32	0.87	1.04	1.01	1.49	1.41	1.11	0.88
1760	1.11	0.73	0.95	0.74	0.52	0.32	1.23	0.61	1.05	1.44
1770	0.82	0.90	0.91	1.70	1.12	1.56	1.33	1.61	1.13	1.49
1780	1.19	1.03	0.86	1.28	0.72	1.23	1.07	0.53	0.26	1.02
1790	0.81	0.96	0.92	1.15	0.90	1.23	1.23	1.36	0.95	0.76
1800	0.75	0.53	1.01	1.04	0.99	0.90	0.42	0.67	0.85	1.05
1810	1.27	1.24	0.80	1.23	1.29	0.96	1.10	1.07	0.93	0.79
1820	0.62	0.40	1.17	0.97	1.04	1.09	0.66	0.42	0.74	1.10
1830	0.69	1.05	0.44	0.67	0.64	0.74	0.48	0.82	0.40	1.14
1840	0.99	1.21	0.78	0.91	0.64	0.89	0.94	1.00	0.63	0.97
1850	0.99	1.17	1.01	0.95	0.80	1.58	1.27	1.26	1.00	0.76
1860	1.35	1.27	1.45	0.90	1.42	1.15	1.75	0.90	1.06	1.13
1870	1.52	1.23	1.05	0.99	1.39	1.26	1.41	1.11	0.86	1.27
1880	0.83	0.88	1.71	1.14	1.45	1.12	1.54	0.56	0.92	0.68
1890	0.98	0.83	0.88	1.25	1.04	0.61	0.74	0.84	0.85	0.85
1900	0.85	0.85	0.83	0.38	0.13	0.41	0.79	0.93	0.68	0.71
1910	0.62	0.97	1.18	0.87	0.99	1.22	0.58	0.55	0.63	0.91
1920	0.79	1.71	0.93	1.86	1.02	1.25	1.02	1.48	0.90	1.23
1930	1.09	1.12	0.83	1.04	0.84	0.91	0.71	1.03	0.87	0.83
1940	1.36	0.80	0.98	1.48	1.26	0.68	1.16	0.29	0.53	1.11
1950	1.44	0.99	1.29	0.70	1.47	1.23	1.03	0.52	0.60	1.00
1960	0.99	1.03	0.95	0.70	0.62	1.13	0.65	0.51	1.09	1.78
1970	1.59	1.60	1.63	1.44	1.15	1.14	0.66	0.36	0.75	1.44
1980	1.52									

The ring width index for each year was derived from 1 radius for the period 1580-1609; 2, 1616-1619; 3, 1620-1629; 4, 1630-1654; 5, 1655-1669; 6, 1670-1728; 7, 1729; 9, 1730-1799; 11, 1800-1829; 13, 1830; 14, 1831-1846; 15, 1847-1900; 11, 1901-1980.

SITE AND COLLECTION INFORMATION

Site name *Lower Cass Valley* Site code *LCV*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'S* Longitude *171°43'E*
Grid reference *NZMS1 S66 193108*
Species collected *Nothofagus solandri*
No. trees sampled *11* No. cores *20* No. discs *0*
Altitude *1350 m* Aspect *N* Slope *20°*
Date of collection *12 February 1981*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located above the junction of Long Valley Stream and the Cass River on the true right-hand (east) side of the Cass River. Access is up the Cass riverbed to the junction, up a small stream initially and then up an obvious avalanche track slightly to the south of the obvious large scree basin. Trees were sampled just south of this avalanche track at timberline starting from the prominent ridge. Trees were sampled a short distance below timberline in monotypic Nothofagus solandri forest with the canopy at about 6 to 8 m. Podocarpus nivalis, Coprosma pseudocuneata and Gaultheria crassa are the main accompanying species.

CHRONOLOGY STATISTICS

Chronology code	*LCV631*	Interval (A.D.)	*1730-1979*
No. trees	*11*	No. radii	*20*
Mean ring width (mm)	*0.79*	% absent rings	*0.70*
Autocorrelation	*0.42*		
Mean sensitivity	*0.35*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

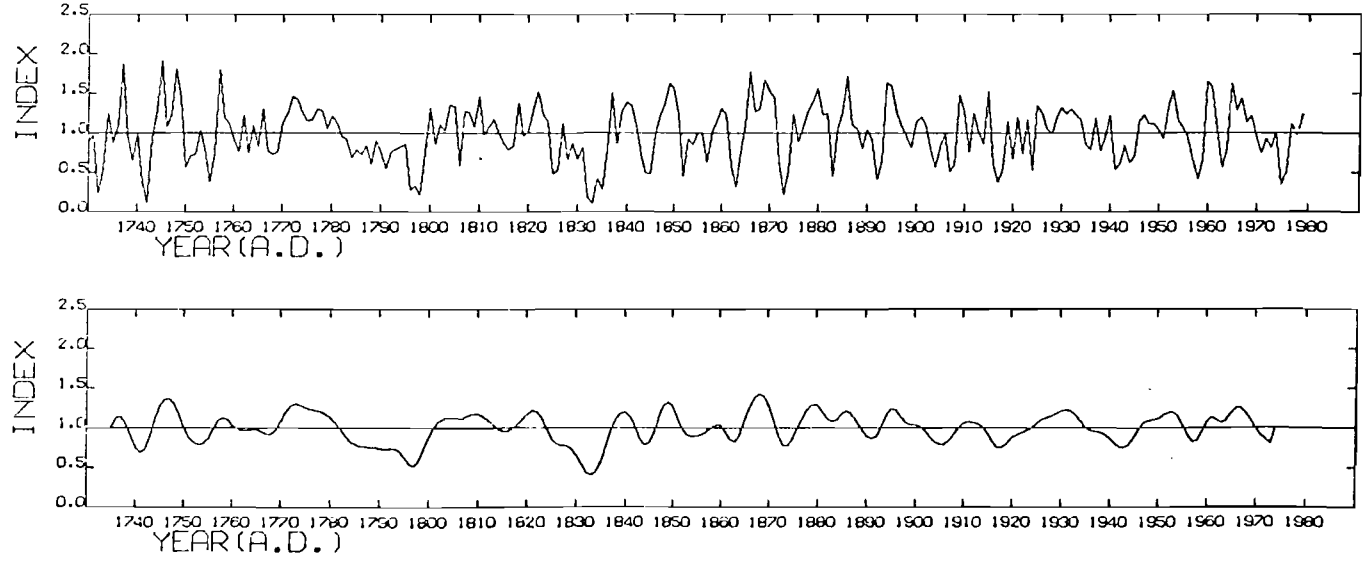
Interval analysed (A.D.) *1840-1979*
No. trees *8* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*44.78*
Differences between trees	*14.18*
Other	*41.04*

Cross-correlation analysis:

Radii within trees	*0.60*
Radii among trees	*0.46*
Between tree means	*0.46*

LCV631 NOTHOFAGUS SOLANDRI CANTERBURY 11 TREES, 20 RADII



LCV631 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1730	0.89	0.98	0.23	0.54	1.25	0.87	1.09	1.87	0.96	0.65
1740	0.99	0.38	0.11	0.93	1.28	1.91	1.07	1.23	1.81	1.42
1750	0.56	0.71	0.72	1.03	0.80	0.37	0.75	1.79	1.18	1.10
1760	0.90	0.76	1.23	0.75	1.10	0.82	1.29	0.77	0.72	0.76
1770	1.12	1.24	1.46	1.41	1.25	1.15	1.16	1.30	1.27	1.04
1780	1.20	1.13	0.96	0.91	0.68	0.78	0.73	0.84	0.59	0.91
1790	0.75	0.54	0.75	0.80	0.82	0.86	0.28	0.32	0.21	0.75
1800	1.31	0.86	1.11	1.02	1.36	1.31	0.59	1.27	1.26	1.07
1810	1.45	0.98	1.07	1.17	0.98	0.86	0.78	0.83	1.38	0.95
1820	1.01	1.29	1.52	1.22	1.13	0.47	0.52	1.12	0.66	0.87
1830	0.65	0.82	0.17	0.10	0.42	0.27	0.80	1.51	0.86	1.29
1840	1.38	1.33	1.10	0.72	0.48	0.47	0.99	1.21	1.36	1.62
1850	1.54	1.24	0.45	0.92	0.85	0.99	1.00	0.63	1.00	1.14
1860	1.31	1.22	0.59	0.31	0.74	1.10	1.78	1.26	1.29	1.67
1870	1.52	1.44	0.64	0.20	0.52	1.23	0.88	1.08	1.27	1.38
1880	1.55	1.22	1.25	0.45	1.06	1.26	1.70	1.09	1.05	0.80
1890	1.03	0.92	0.41	0.65	1.64	1.58	1.25	1.07	0.95	0.81
1900	1.13	1.19	1.10	0.78	0.56	0.83	0.98	0.51	0.60	1.48
1910	1.26	0.75	1.25	1.01	0.86	1.52	0.60	0.37	0.54	1.14
1920	0.67	1.19	0.73	1.17	0.52	1.34	1.25	1.05	0.99	1.19
1930	1.32	1.23	1.29	1.22	1.15	0.84	0.78	1.18	0.77	0.95
1940	1.22	0.53	0.61	0.83	0.62	0.69	1.15	1.22	1.11	1.10
1950	1.03	0.92	1.31	1.53	1.14	1.07	0.93	0.65	0.41	0.64
1960	1.64	1.57	1.04	0.56	0.81	1.62	1.27	1.44	1.13	1.20
1970	0.93	0.73	0.92	0.79	1.01	0.33	0.50	1.11	0.96	1.23

The ring width index for each year was derived from 1 radius for the period 1730-1739; 2, 1740-1752; 3, 1753-1759; 4, 1760-1763; 5, 1764; 6, 1765-1769; 7, 1770-1772; 8, 1773-1789; 9, 1790-1799; 12, 1800-1830; 13, 1831-1832; 14, 1833-1839; 18, 1840-1868; 19, 1869-1879; 20, 1880-1979.

Site name *Logos Hill 1* Site code *LGH1*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'S* Longitude *171°42'E*
Grid reference *NZMS1 S66 172109*
Species collected *Nothofagus solandri*
No. trees sampled *15* No. cores *15* No. discs *0*
Altitude *1400 m* Aspect *N* Slope *30°*
Date of collection *10 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station, Cass.

This site is located in gnarled subalpine forest immediately below timberline. The trees are of multileader coppice growth form and the canopy is at about 3-4 m. Several subalpine species occur within the forest including Podocarpus nivalis, Coprosma c.f. pseudocuneata, Gaultheria crassa, Celmisia spectabilis and Phyllocladus alpinus. The substrate is rocky and well drained.

CHRONOLOGY STATISTICS

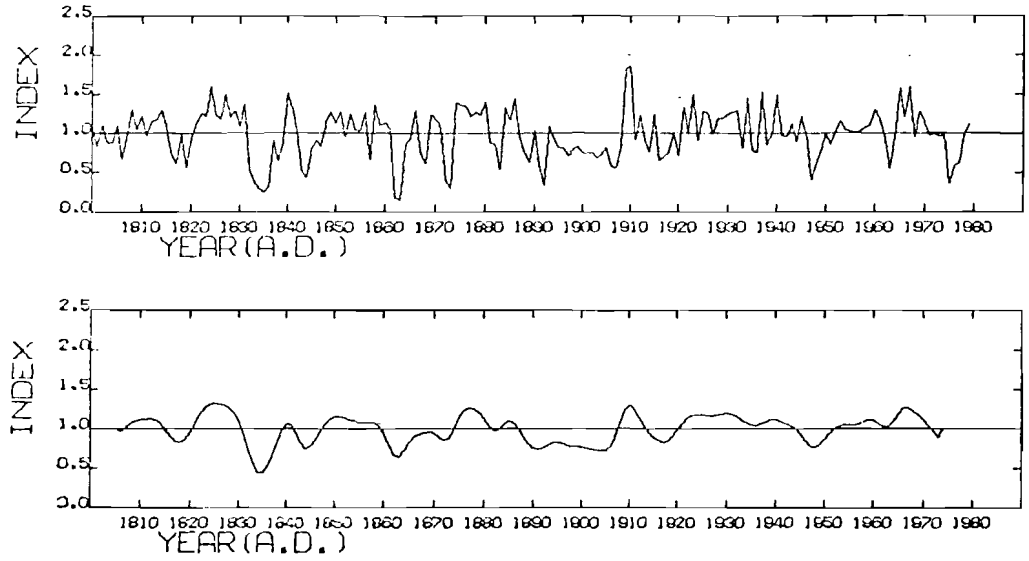
Chronology code	*LGH617*	Interval (A.D.)	*1800-1979*
No. trees	*13*	No. radii	*13*
Mean ring width (mm)	*0.87*	% absent rings	*0.18*
Autocorrelation	*0.38*		
Mean sensitivity	*0.29*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

Interval analysed (A.D.) *1930-1979*
No. trees *13* No. radii *1*
Analysis of variance (% variance explained):

Mean chronology	-
Differences between trees	-
Other	-
Cross-correlation analysis:	
Radii within trees	*0.42*
Radii among trees	*0.39*
Between tree means	*0.40*

LGH617 NOTHOFAGUS SOLANDRI 13 TREES, 13 RADII



LGH617 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1800	1.10	0.82	1.10	0.88	0.87	1.10	0.66	0.99	1.29	1.03
1810	1.21	0.95	1.14	1.17	1.28	1.06	0.72	0.61	1.00	0.56
1820	0.94	1.12	1.24	1.21	1.59	1.23	1.17	1.50	1.20	1.28
1830	1.08	1.37	0.53	0.39	0.29	0.25	0.31	0.91	0.64	0.87
1840	1.51	1.33	1.04	0.52	0.43	0.80	0.89	0.83	1.13	1.27
1850	1.12	1.27	0.95	1.24	1.04	1.02	1.27	0.66	1.36	1.10
1860	1.12	1.06	0.19	0.14	0.85	0.94	1.30	0.73	0.61	1.24
1870	1.17	1.07	0.39	0.30	1.39	1.36	1.33	1.21	1.26	1.22
1880	1.40	0.87	0.85	0.53	1.33	1.16	1.43	0.95	0.74	0.62
1890	1.03	0.58	0.34	1.09	0.93	0.81	0.80	0.71	0.78	0.83
1900	0.74	0.75	0.75	0.68	0.72	0.81	0.58	0.55	0.83	1.81
1910	1.85	0.91	1.23	0.91	0.76	1.23	0.64	0.70	0.74	1.01
1920	0.71	1.33	1.01	1.49	0.91	1.27	1.25	0.98	1.18	1.18
1930	1.23	1.26	1.28	0.80	1.44	0.79	0.74	1.52	0.84	0.99
1940	1.49	0.98	0.95	1.12	0.88	1.21	0.98	0.40	0.61	0.78
1950	1.00	0.86	1.02	1.16	1.05	1.02	1.03	1.02	1.07	1.09
1960	1.29	1.18	0.99	0.55	0.96	1.58	1.19	1.60	0.94	1.27
1970	1.15	0.97	0.98	0.95	0.97	0.35	0.56	0.62	0.97	1.11

The ring width index for each year was derived from 1 radius for the period 1800-1839; 2, 1840-1859; 3, 1860-1869; 4, 1870-1879; 6, 1880-1899; 7, 1900-1924; 8, 1925-1929; 13, 1930-1979.

SITE AND COLLECTION INFORMATION

Site name *Logos Hill 2* Site code *LGH2*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'S* Longitude *171°42'E*
Grid reference *NZMS1 S66 175113*
Species collected *Nothofagus solandri*
No. trees sampled *11* No. cores *20* No. discs *0*
Altitude *1300 m* Aspect *E* Slope *30°*
Date of collection *10 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

This site is located below timberline on a broad shoulder at the point where the main ridge divides. Tall erect Nothofagus solandri forest is present and the canopy is at about 8m. The trees are of a predominantly single leader growth form and seedlings and saplings are present. Podocarpus nivalis and Coprosma c.f. pseudocuneata are common.

CHRONOLOGY STATISTICS

Chronology code	*LGH618*	Interval (A.D.)	*1740-1979*
No. trees	*11*	No. radii	*20*
Mean ring width (mm)	*0.66*	% absent rings	*2.30*
Autocorrelation	*0.50*		
Mean sensitivity	*0.40*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

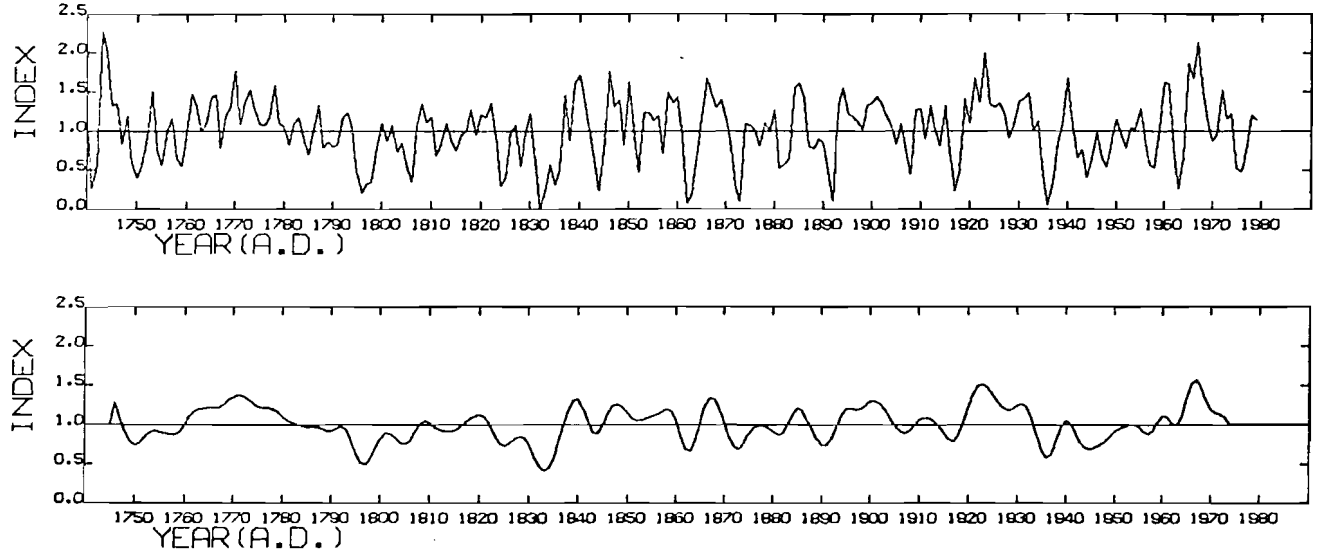
Interval analysed (A.D.) *1890-1979*
No. trees *9* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*41.30*
Differences between trees	*22.21*
Other	*36.49*

Cross-correlation analysis:

Radii within trees	*0.66*
Radii among trees	*0.50*
Between tree means	*0.51*

LGH618 NOTHOFAGUS SOLANDRI CANTERBURY 11 TREES, 20RADII



LGH618 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1740	1.10	0.26	0.56	2.28	1.99	1.33	1.35	0.83	1.18	0.54
1750	0.39	0.57	0.92	1.51	0.76	0.56	1.01	1.16	0.64	0.54
1760	1.00	1.46	1.30	1.00	1.10	1.42	1.46	0.78	1.19	1.32
1770	1.78	1.08	1.37	1.52	1.28	1.08	1.06	1.17	1.58	1.09
1780	1.05	0.83	1.09	1.18	0.91	0.69	1.01	1.33	0.78	0.86
1790	0.80	0.82	1.18	1.23	1.01	0.46	0.21	0.31	0.34	0.78
1800	1.09	0.88	1.07	0.73	0.84	0.56	0.34	1.07	1.34	1.11
1810	1.18	0.69	0.83	1.10	0.89	0.75	0.95	1.01	1.27	0.95
1820	1.21	1.16	1.36	0.92	0.29	0.40	0.98	1.07	0.54	0.98
1830	1.22	0.60	0.01	0.22	0.57	0.31	0.52	1.46	0.88	1.61
1840	1.70	1.38	1.02	0.64	0.23	0.89	1.76	1.31	1.40	0.82
1850	1.63	1.03	0.47	1.23	1.23	1.13	1.20	0.71	1.49	1.36
1860	1.44	0.93	0.07	0.19	0.67	1.17	1.68	1.47	1.29	1.40
1870	1.17	0.87	0.31	0.09	1.09	1.07	1.01	0.81	1.10	1.00
1880	1.26	0.52	0.57	0.64	1.55	1.61	1.42	0.80	0.77	0.90
1890	0.85	0.48	0.11	1.35	1.55	1.22	1.17	1.10	1.02	1.32
1900	1.36	1.44	1.34	1.19	1.07	0.83	1.09	0.74	0.45	1.27
1910	1.28	0.89	1.32	1.01	0.81	1.33	0.73	0.24	0.50	1.41
1920	1.10	1.67	1.36	1.99	1.34	1.30	1.36	1.22	0.91	1.08
1930	1.37	1.41	1.48	1.01	1.12	0.43	0.05	0.34	0.84	1.13
1940	1.67	1.05	0.66	0.76	0.39	0.66	0.98	0.65	0.54	0.87
1950	1.15	0.96	0.79	1.03	1.03	1.28	0.91	0.56	0.52	1.04
1960	1.62	1.60	0.79	0.25	0.66	1.86	1.68	2.13	1.49	1.15
1970	0.88	0.95	1.52	1.16	1.22	0.52	0.48	0.74	1.20	1.13

The ring width index for each year was derived from 1 radius for the period 1740-1757; 2, 1758-1764; 4, 1765-1779; 6, 1780-1799; 10, 1800-1809; 12, 1810-1812; 13, 1813-1819; 14, 1820-1825; 15, 1826-1839; 17, 1840-1849; 18, 1850-1859; 19, 1860-1869; 20, 1870-1979.

SITE AND COLLECTION INFORMATION

Site name *Logos Hill 3* Site code *LGH3*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'* Longitude *171°42'E*
Grid reference *NZMS1 S66 179113*
Species collected *Nothofagus solandri*
No. trees sampled *16* No. cores *28* No. discs *0*
Altitude *1200 m* Aspect *SE* Slope *25°*
Date of collection *12 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

This site is located on a moderately well drained southeast facing slope immediately below the ridge crest. Tall erect Nothofagus solandri trees form the canopy at 10-12 m. Associated species include Podocarpus nivalis, Pseudopanax colensoi, Coprosma species and the ferns, Hymenophyllum spp., Blechnum penna-marina and Polystichum vestitum. N.solandri regeneration is present.

CHRONOLOGY STATISTICS

Chronology code	*LGH619*	Interval (A.D.)	*1740-1979*
No. trees	*16*	No. radii	*25*
Mean ring width (mm)	*1.08*	% absent rings	*2.14*
Autocorrelation	*0.55*		
Mean sensitivity	*0.33*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

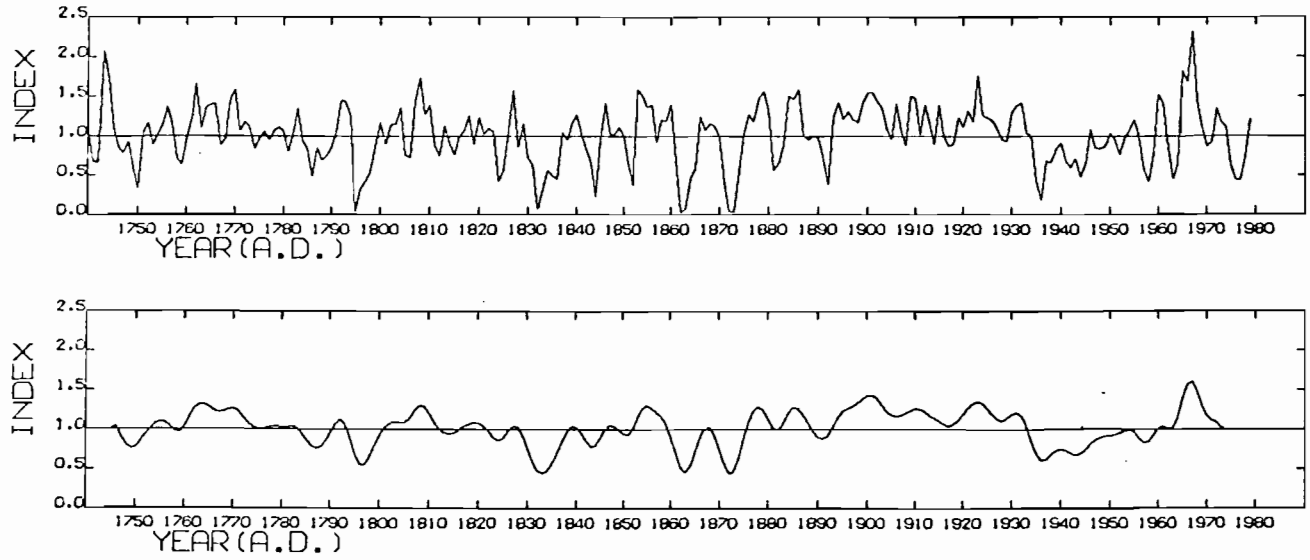
Interval analysed (A.D.) *1890-1979*
No. trees *9* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*35.85*
Differences between trees	*28.01*
Other	*36.14*

Cross-correlation analysis:

Radii within trees	*0.67*
Radii among trees	*0.44*
Between tree means	*0.45*

LGH619 NOTHOFAGUS SOLANDRI CANTERBURY 16 TREES, 25 RADII



LGH619 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1740	1.08	0.67	0.65	2.07	1.72	1.10	0.85	0.78	0.93	0.60
1750	0.33	1.04	1.16	0.89	1.02	1.15	1.37	1.15	0.71	0.63
1760	0.97	1.21	1.66	1.10	1.36	1.39	1.41	0.88	0.96	1.47
1770	1.58	1.06	1.18	1.11	0.83	0.98	1.06	0.94	1.07	1.11
1780	1.06	0.80	1.03	1.36	0.93	0.83	0.48	0.85	0.68	0.75
1790	0.85	1.04	1.46	1.43	1.24	0.04	0.32	0.42	0.54	0.87
1800	1.18	0.89	1.15	1.14	1.36	0.74	0.72	1.45	1.73	1.27
1810	1.39	0.86	0.75	1.14	0.91	0.76	0.99	1.05	1.26	0.89
1820	1.23	1.03	1.09	1.04	0.43	0.57	1.09	1.57	0.85	1.16
1830	0.71	0.64	0.07	0.32	0.56	0.50	0.44	1.05	0.94	1.16
1840	1.28	1.01	0.82	0.64	0.22	0.95	1.43	1.03	1.02	1.11
1850	1.01	0.64	0.37	1.59	1.51	1.35	1.39	0.92	1.21	1.18
1860	1.40	0.68	0.02	0.07	0.45	0.60	1.25	1.07	1.15	1.11
1870	0.98	0.40	0.03	0.04	0.56	1.03	1.27	1.18	1.48	1.56
1880	1.30	0.56	0.64	0.88	1.51	1.46	1.58	1.00	0.95	1.01
1890	0.98	0.70	0.39	1.24	1.42	1.21	1.31	1.20	1.17	1.41
1900	1.55	1.54	1.43	1.35	1.10	0.96	1.40	1.06	0.88	1.51
1910	1.47	1.02	1.40	1.17	0.90	1.39	0.99	0.88	0.90	1.23
1920	1.11	1.31	1.18	1.76	1.26	1.23	1.20	1.09	0.94	0.94
1930	1.30	1.38	1.42	1.03	1.01	0.42	0.18	0.68	0.66	0.83
1940	0.91	0.69	0.59	0.70	0.47	0.64	1.08	0.84	0.83	0.87
1950	1.04	0.94	0.76	0.98	1.06	1.21	0.98	0.57	0.41	0.78
1960	1.52	1.41	0.85	0.44	0.65	1.82	1.68	2.32	1.45	1.11
1970	0.86	0.92	1.35	1.17	1.11	0.62	0.43	0.43	0.73	1.21

The ring width index for each year was derived from 1 radius for the period 1740-1759; 3, 1760-1795; 4, 1796-1799; 8, 1800-1809; 9, 1810-1819; 11, 1820-1829; 12, 1830-1839; 17, 1840-1849; 18, 1850-1879; 23, 1880-1889; 25, 1890-1945; 24, 1946-1975; 23, 1976-1979.

SITE AND COLLECTION INFORMATION

Site name	*Logos Hill 4*	Site code	*LGH4*
Location	*Craigieburn Range, Canterbury*		
Latitude	*43°05'S*	Longitude	*171°42'E*
Grid reference	*NZMS1 S66 181114*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*12*	No. cores *24*	No. discs *0*
Altitude	*1100 m*	Aspect *NE*	Slope *25°*
Date of collection	*12 December 1980*		
Collectors	*D.A.Norton and A.E.Moore*		

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

This site is located on a broad slope where the ridge widens below an area of eroded bedrock (facing into the Cass River). The Nothofagus solandri forest is fairly open with the canopy at between 9 and 11 m. N.solandri regeneration is abundant, particularly below canopy gaps, and Gaultheria antipoda is the most common shrub species present.

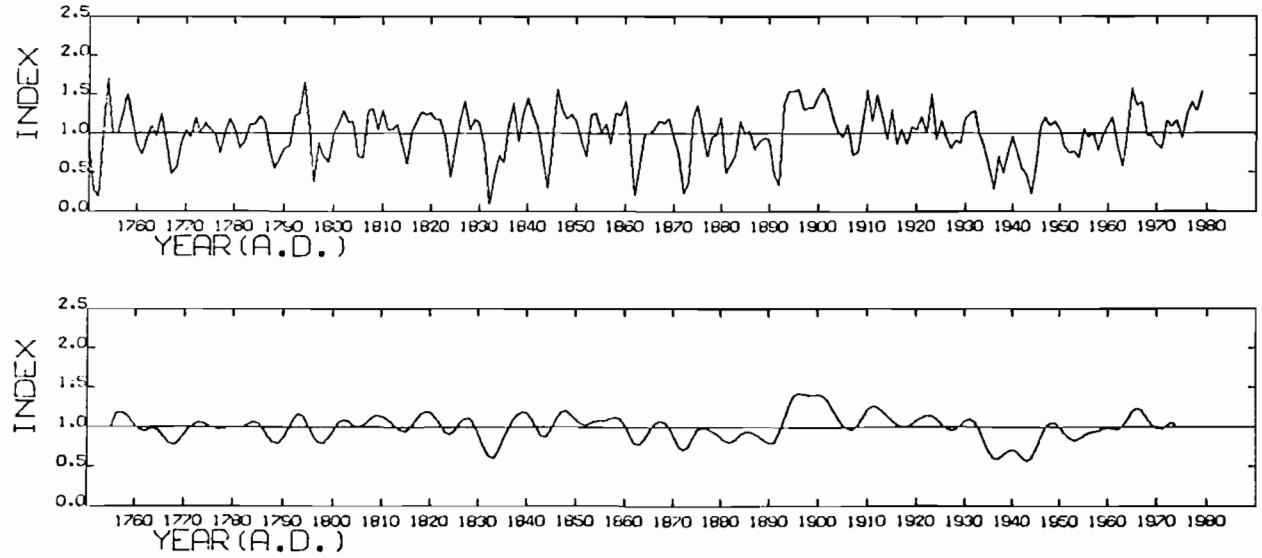
CHRONOLOGY STATISTICS

Chronology code	*LGH620*	Interval (A.D.)	*1745-1979*
No. trees	*11*	No. radii	*21*
Mean ring width (mm)	*0.95*	% absent rings	*0.53*
Autocorrelation	*0.49*		
Mean sensitivity	*0.29*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

Interval analysed (A.D.)	*1890-1979*		
No. trees	*7*	No. radii	*2*
Analysis of variance (% variance explained):			
Mean chronology	*36.08*		
Differences between trees	*3.14*		
Other	*60.78*		
Cross-correlation analysis:			
Radii within trees	*0.43*		
Radii among trees	*0.39*		
Between tree means	*0.39*		

LGH620 NOTHOFAGUS SOLANDRI CANTERBURY 11 TREES, 21RADII



LGH620 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1745						1.41	1.27	0.65	1.67	1.35
1750	0.83	0.26	0.18	1.00	1.70	0.98	0.99	1.22	1.51	1.17
1760	0.85	0.72	0.93	1.08	0.96	1.24	0.88	0.47	0.55	0.86
1770	1.04	0.93	1.20	1.00	1.13	1.04	0.98	0.73	1.00	1.18
1780	1.05	0.80	0.90	1.11	1.10	1.20	1.16	0.79	0.53	0.67
1790	0.81	0.83	1.20	1.26	1.65	1.05	0.36	0.88	0.69	0.61
1800	1.01	1.11	1.29	1.14	1.15	0.70	0.69	1.30	1.31	1.03
1810	1.29	1.04	1.04	1.11	0.87	0.59	1.00	1.14	1.27	1.23
1820	1.26	1.16	1.17	0.91	0.44	0.84	1.17	1.40	1.03	1.17
1830	1.12	0.85	0.09	0.44	0.70	0.63	1.09	1.39	0.88	1.24
1840	1.44	1.23	1.07	0.66	0.29	0.87	1.56	1.29	1.17	1.23
1850	1.15	0.88	0.69	1.23	1.26	0.99	1.12	0.86	1.26	1.23
1860	1.41	0.92	0.19	0.58	0.98	1.00	1.04	1.14	1.12	1.19
1870	0.95	0.74	0.22	0.36	1.17	1.36	1.02	0.70	0.95	0.97
1880	1.20	0.48	0.59	0.73	1.15	0.99	1.02	0.78	0.88	0.94
1890	0.91	0.46	0.33	1.37	1.54	1.53	1.56	1.29	1.32	1.32
1900	1.47	1.57	1.44	1.18	1.02	0.95	1.11	0.71	0.76	1.13
1910	1.55	1.15	1.48	1.22	0.90	1.30	0.84	1.04	0.84	1.08
1920	1.03	1.20	0.99	1.49	0.91	1.15	0.95	0.80	0.89	0.86
1930	1.18	1.24	1.28	0.97	0.83	0.56	0.28	0.71	0.48	0.73
1940	0.96	0.76	0.55	0.47	0.22	0.57	1.08	1.19	1.10	1.14
1950	1.05	0.82	0.75	0.76	0.68	1.06	0.94	1.00	0.76	0.97
1960	1.09	1.20	0.82	0.57	1.00	1.58	1.34	1.40	0.96	0.64
1970	0.85	0.79	1.16	1.09	1.15	0.93	1.25	1.39	1.28	1.53

The ring width index for each year was derived from 1 radius for the period 1745-1759; 2, 1760-1769; 3, 1770-1778; 4, 1779; 5, 1780-1809; 7, 1810-1819; 9, 1820-1839; 10, 1840-1849; 14, 1850-1859; 16, 1860-1869; 17, 1870-1879; 19, 1880-1899; 21, 1900-1930; 20, 1931-1979.

SITE AND COLLECTION INFORMATION

Site name	*Logos Hill 5*	Site code	*LGH5*
Location	*Craigieburn Range, Canterbury*		
Latitude	*43°05'S*	Longitude	*171°42'E*
Grid reference	*NZMS1 S66 183117*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*14*	No. cores *27*	No. discs *0*
Altitude	*100 m*	Aspect *SE*	Slope *5°*
Date of collection	*9 January 1981*		
Collectors	*D.A.Norton and A.E.Moore*		

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

This site is located on the southeast side of the ridge on a gentle slope with only poor to moderate drainage. Tall (10-12 m) Nothofagus solandri forest occurs above prolific N. solandri regeneration. No other species are conspicuous.

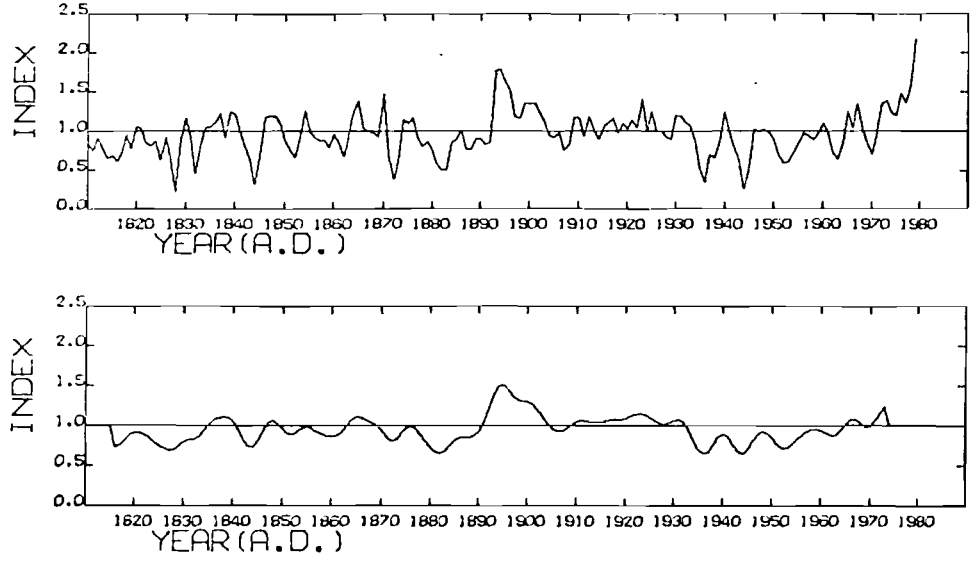
CHRONOLOGY STATISTICS

Chronology code	*LGH621*	Interval (A.D.)	*1810-1979*
No. trees	*14*	No. radii	*27*
Mean ring width (mm)	*1.19*	% absent rings	*0.25*
Autocorrelation	*0.64*		
Mean sensitivity	*0.21*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

Interval analysed (A.D.)	*1890-1979*
No. trees	*9*
No. radii	*2*
Analysis of variance (% variance explained):	
Mean chronology	*31.30*
Differences between trees	*35.99*
Other	*32.71*
Cross-correlation analysis:	
Radii within trees	*0.63*
Radii among trees	*0.37*
Between tree means	*0.38*

LGH621 NOTHOFAGUS SOLANDRI CANTERBURY 14 TREES, 27 RADII



LGH621 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1810	0.84	0.75	0.91	0.76	0.64	0.67	0.60	0.73	0.95	0.77
1820	1.04	1.03	0.85	0.80	0.86	0.62	0.92	0.63	0.20	0.87
1830	1.16	0.90	0.44	0.80	1.04	1.05	1.11	1.23	0.91	1.25
1840	1.21	0.99	0.80	0.63	0.31	0.68	1.17	1.19	1.19	1.09
1850	0.89	0.75	0.66	0.94	1.26	1.00	0.91	0.87	0.88	0.79
1860	0.96	0.83	0.68	0.94	1.23	1.38	1.04	0.98	0.97	0.92
1870	1.48	0.68	0.37	0.61	1.15	1.10	1.16	0.91	0.80	0.86
1880	0.76	0.57	0.50	0.50	0.85	0.89	1.01	0.76	0.76	0.90
1890	0.90	0.82	0.86	1.76	1.79	1.62	1.49	1.17	1.16	1.36
1900	1.35	1.35	1.23	1.13	0.93	0.90	0.97	0.74	0.82	1.17
1910	1.17	0.91	1.19	1.02	0.89	1.05	1.10	1.15	0.97	1.09
1920	1.02	1.13	1.03	1.41	1.00	1.25	0.98	0.99	0.92	0.89
1930	1.19	1.19	1.11	1.06	0.87	0.52	0.33	0.69	0.65	0.87
1940	1.23	0.96	0.79	0.61	0.24	0.49	1.01	0.98	1.02	0.98
1950	0.89	0.69	0.58	0.61	0.73	0.84	0.97	0.93	0.89	0.96
1960	1.09	0.99	0.73	0.63	0.83	1.24	1.03	1.35	1.02	0.82
1970	0.69	0.99	1.35	1.38	1.22	1.19	1.47	1.35	1.57	2.17

The ring width index for each year was derived from 1 radius for the period 1810-1829; 4, 1830-1859; 5, 1860-1869; 6, 1870-2874; 8, 1876-1879; 16, 1880-1889;23, 1890; 24, 1891-1892; 25, 1893-1899; 27, 1900-1979.

SITE AND COLLECTION INFORMATION

Site name	*Logos Hill 6*	Site code	*LGH6*
Location	*Craigieburn Range, Canterbury*		
Latitude	*43°05'S*	Longitude	*171°42'E*
Grid reference	*NZMS1 S66 185118*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*14*	No. cores *23*	No. discs *0*
Altitude	*900 m*	Aspect *N*	Slope *30°*
Date of collection	*9 January 1981*		
Collectors	*D.A.Norton and A.E.Moore*		

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

Slightly stunted Nothofagus solandri trees grow on this well drained ridge crest site. The canopy is at about 8-12 m. Other species present include Cyathodes juniperina, Gaultheria antipoda, Aristotelia fruticosa, Podocarpus hallii (stunted), Coprosma microcarpa, C.linarifolia and Phyllocladus alpinus.

CHRONOLOGY STATISTICS

Chronology code	*LGH622*	Interval (A.D.)	*1800-1979*
No. trees	*11*	No. radii	*21*
Mean ring width (mm)	*0.90*	% absent rings	*0.04*
Autocorrelation	*0.50*		
Mean sensitivity	*0.21*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

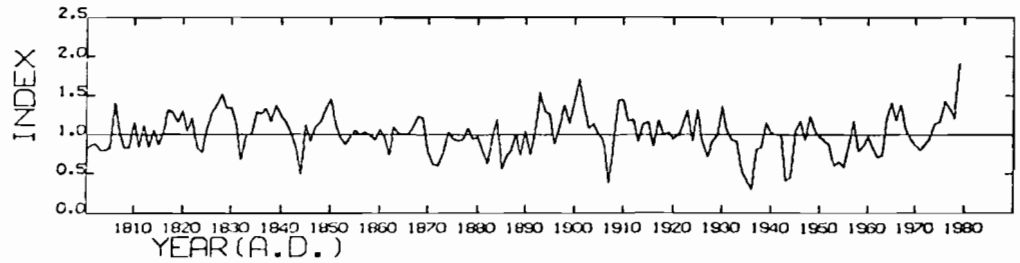
Interval analysed (A.D.) *1890-1979*
No. trees *10* No. radii *2*
Analysis of variance (% variance explained):

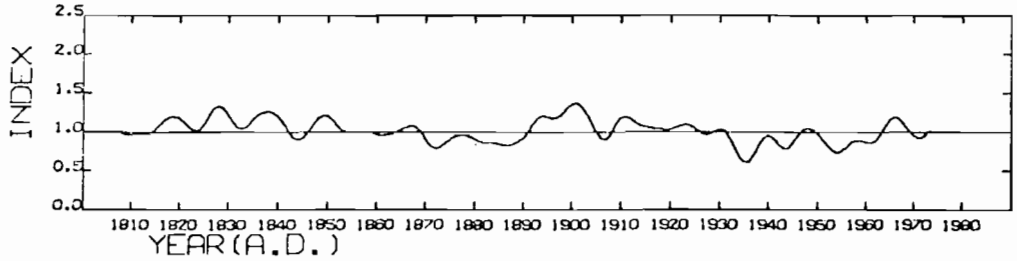
Mean chronology	*28.78*
Differences between trees	*15.96*
Other	*55.26*

Cross-correlation analysis:

Radii within trees	*0.53*
Radii among trees	*0.34*
Between tree means	*0.35*

LGH622 NOTHOFAGUS SOLANDRI CANTERBURY 11 TREES, 21 RADII





LGH622 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1800	0.80	0.86	0.88	0.78	0.80	0.83	1.40	1.04	0.82	0.83
1810	1.16	0.83	1.12	0.83	1.06	0.86	1.04	1.33	1.28	1.14
1820	1.31	1.03	1.21	0.82	0.75	1.06	1.28	1.37	1.52	1.33
1830	1.34	1.11	0.67	0.99	0.99	1.28	1.26	1.33	1.16	1.38
1840	1.24	1.15	1.01	0.82	0.49	1.11	0.91	1.10	1.16	1.33
1850	1.46	1.14	0.96	0.87	0.97	1.05	0.98	1.04	0.98	0.92
1860	1.07	0.95	0.73	1.09	1.00	1.01	1.01	1.10	1.24	1.21
1870	0.79	0.61	0.59	0.76	1.04	0.93	0.92	0.93	1.08	0.93
1880	0.97	0.80	0.62	0.97	1.19	0.56	0.73	0.81	1.01	0.72
1890	1.04	0.73	1.03	1.54	1.28	1.26	0.87	1.10	1.38	1.14
1900	1.41	1.72	1.37	1.07	1.13	1.00	0.91	0.37	0.85	1.45
1910	1.44	1.16	1.20	0.91	1.13	1.15	0.84	1.18	1.00	1.03
1920	0.94	1.00	1.12	1.31	0.90	1.32	0.88	0.71	0.91	0.99
1930	1.36	1.04	0.92	0.91	0.53	0.39	0.30	0.80	0.83	1.15
1940	1.01	0.99	0.99	0.40	0.45	1.04	1.17	0.92	1.24	1.05
1950	0.96	0.91	0.86	0.59	0.64	0.57	0.86	1.17	0.78	0.85
1960	0.97	0.83	0.70	0.73	1.22	1.41	1.17	1.38	1.06	0.93
1970	0.86	0.79	0.87	0.96	1.14	1.15	1.42	1.33	1.19	1.91

The ring width index for each year was derived from 1 radius for the period 1800-1809; 2, 1810-1819; 4, 1820-1829; 7, 1830-1839; 10, 1840-1849; 15, 1850-1859; 17, 1860-1869; 20, 1870-1879; 21, 1880-1979.

SITE AND COLLECTION INFORMATION

Site name	*Logos Hill 7*	Site code	*LGH7*
Location	*Craigieburn Range, Canterbury*		
Latitude	*43°05'S*	Longitude	*171°42'E*
Grid reference	*NZMS1 S66 188120*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*10*	No. cores *20*	No. discs *0*
Altitude	*800 m*	Aspect *SE*	Slope *0°*
Date of collection	*9 January 1981*		
Collectors	*D.A.Norton and A.E.Moore*		

Site description:

Logos Hill is located in the Cass Valley, Craigieburn Forest Park. Seven sites (LGH1 to LGH7) were sampled along a ridge descending northeast from Logos Hill, terminating at the junction of the Cass River and Long Valley Stream. Access to this area is up the Cass River from the University of Canterbury Field Station.

This site is located adjacent to the Cass River upstream (about 200 m) from the Long Valley Stream junction on the first forested terrace on the true right-hand side of the river. Tall (10-14 m) Nothofagus solandri forest grows on this moderately drained terrace with a diverse and dense understorey including Coprosma spp., Phyllocladus alpinus and Rubus spp. A deep layer of moss is present on the forest floor.

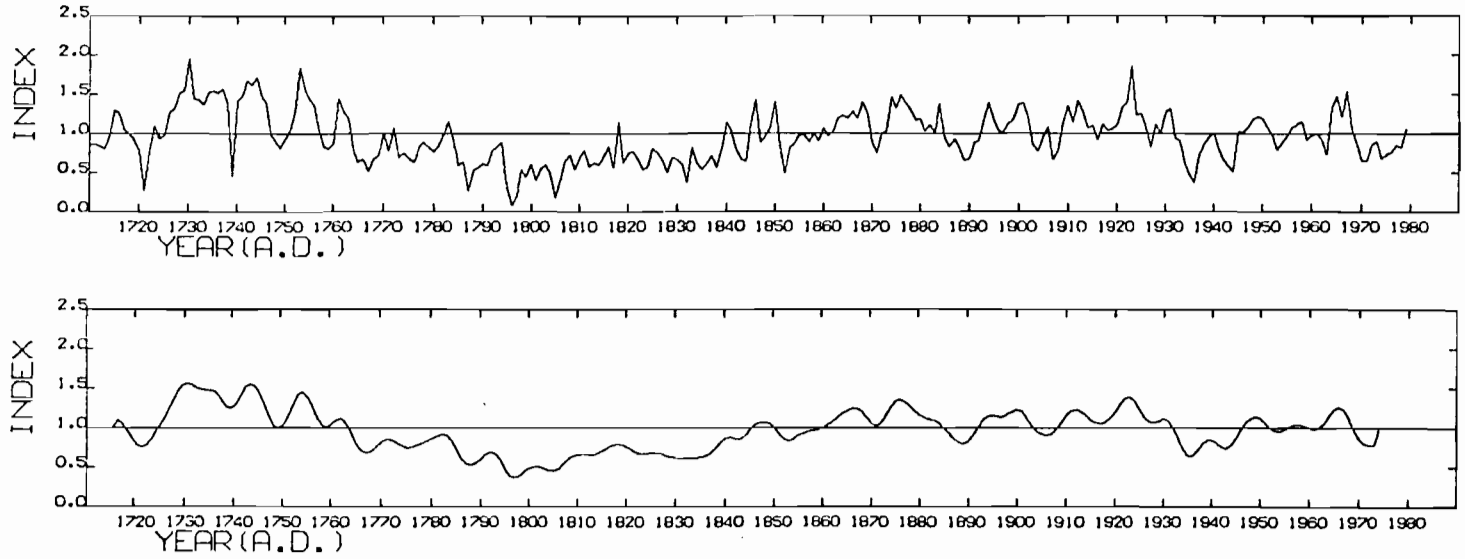
CHRONOLOGY STATISTICS

Chronology code	*LGH623*	Interval (A.D.)	*1710-1979*
No. trees	*7*	No. radii	*13*
Mean ring width (mm)	*0.82*	% absent rings	*0.21*
Autocorrelation	*0.74*		
Mean sensitivity	*0.21*		
Mean standard error	*0.15*		

SAMPLE STATISTICS

Interval analysed (A.D.)	*1890-1979*		
No. trees	*5*	No. radii	*2*
Analysis of variance (% variance explained):			
Mean chronology	*28.82*		
Differences between trees	*23.23*		
Other	*47.95*		
Cross-correlation analysis:			
Radii within trees	*0.51*		
Radii among trees	*0.30*		
Between tree means	*0.32*		

LGH623 NOTHOFAGUS SOLANDRI CANTERBURY 7 TREES, 13RADII



LGH623 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1710	0.86	0.86	0.84	0.80	0.97	1.30	1.25	1.04	1.00	0.90
1720	0.77	0.26	0.77	1.10	0.91	0.97	1.26	1.30	1.51	1.53
1730	1.95	1.44	1.41	1.36	1.52	1.54	1.51	1.56	1.37	0.45
1740	1.41	1.47	1.67	1.60	1.71	1.47	1.38	0.98	0.90	0.81
1750	0.91	1.03	1.25	1.84	1.57	1.43	1.35	1.05	0.84	0.79
1760	0.86	1.44	1.29	1.19	0.80	0.62	0.68	0.51	0.67	0.71
1770	0.99	0.78	1.07	0.68	0.74	0.68	0.62	0.82	0.88	0.82
1780	0.75	0.85	0.98	1.15	0.92	0.59	0.63	0.26	0.53	0.56
1790	0.61	0.58	0.78	0.82	0.89	0.29	0.07	0.20	0.53	0.43
1800	0.61	0.40	0.55	0.60	0.47	0.17	0.39	0.64	0.72	0.53
1810	0.68	0.78	0.57	0.62	0.60	0.69	0.84	0.56	1.14	0.62
1820	0.74	0.78	0.66	0.54	0.57	0.81	0.75	0.65	0.49	0.70
1830	0.66	0.60	0.37	0.82	0.61	0.53	0.61	0.70	0.55	0.79
1840	1.13	1.00	0.78	0.66	0.63	1.12	1.43	0.87	0.96	1.08
1850	1.40	0.83	0.48	0.80	0.85	0.97	0.96	0.89	0.99	0.90
1860	1.06	0.95	1.02	1.18	1.22	1.19	1.27	1.19	1.40	1.25
1870	0.87	0.74	1.00	1.03	1.46	1.31	1.48	1.38	1.29	1.15
1880	1.18	1.02	1.09	1.01	1.36	0.93	0.82	0.93	0.80	0.65
1890	0.67	0.87	0.90	1.17	1.38	1.18	1.02	1.02	1.13	1.18
1900	1.37	1.39	1.19	0.84	0.76	0.94	1.08	0.66	0.76	1.13
1910	1.34	1.13	1.40	1.26	1.06	1.10	0.91	1.11	1.03	1.04
1920	1.10	1.32	1.38	1.85	1.22	1.25	1.05	0.83	1.11	1.00
1930	1.26	1.31	0.94	0.90	0.62	0.47	0.37	0.73	0.86	0.95
1940	1.00	0.80	0.65	0.59	0.51	1.02	1.01	1.07	1.17	1.21
1950	1.19	1.07	0.97	0.78	0.87	0.96	1.07	1.11	1.15	0.91
1960	0.97	0.99	0.91	0.72	1.33	1.48	1.20	1.53	1.07	0.88
1970	0.65	0.65	0.85	0.89	0.67	0.72	0.76	0.84	0.81	1.06

The ring width index for each year was derived from 1 radius for the period 1710-1729; 2, 1730-1809; 3, 1810-1829; 4, 1830-1839; 5, 1840-1849; 7, 1850-1859; 10, 1860-1869; 12, 1870-1895; 13, 1896-1979.

Site name *Lagoon Saddle* Site code *LGS*
Location *Craigieburn Range, Canterbury*
Latitude *43°03'S* Longitude *171°36'E*
Grid reference *NZMS1 S66 094147*
Species collected *Nothofagus solandri*
No. trees sampled *15* No. cores *28* No. discs *0*
Altitude *1300 m* Aspect *SW* Slope *15°*
Date of collection *12 January 1981*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Lagoon Saddle lies between Bruce Stream (a tributary of the Waimakariri River) and the Harper River, in Craigieburn Forest Park. Access is on foot from State Highway 73 near Bealey. The site is located near timberline east of Lagoon Saddle on the slopes of Mount Bruce. The monotypic Nothofagus solandri forest up to 8 m tall grows on a poorly to moderately drained substrate. Fire has probably affected the forest margin; adjacent slopes are now forest free. Associated species include abundant Podocarpus nivalis with Coprosma species, Gaultheria crassa, Hebe brachysiphon, Phyllocladus alpinus and various herbaceous species and ferns.

CHRONOLOGY STATISTICS

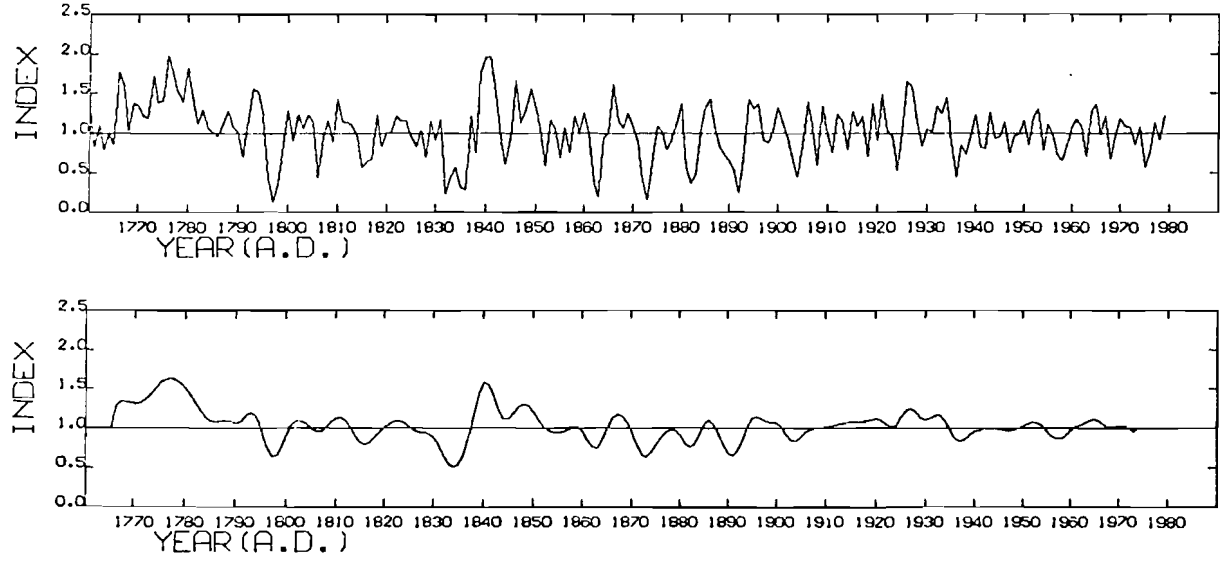
Chronology code	*LGS624*	Interval (A.D.)	*1760-1979*
No. trees	*15*	No. radii	*28*
Mean ring width (mm)	*0.75*	% absent rings	*1.43*
Autocorrelation	*0.46*		
Mean sensitivity	*0.33*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

Interval analysed (A.D.) *1850-1979*
No. trees *9* No. radii
Analysis of variance (% variance explained):
- Mean chronology *35.65*
- Differences between trees *13.91*
- Other *50.44*

Cross-correlation analysis:
- Radii within trees *0.56*
- Radii among trees *0.39*
- Between tree means *0.40*

LGS624 NOTHOFAGUS SOLANDRI CANTERBURY 15 TREES, 28RADII



LGS624 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1760	1.27	0.82	1.09	0.78	1.00	0.85	1.78	1.60	1.02	1.37
1770	1.35	1.21	1.18	1.72	1.38	1.39	1.99	1.73	1.51	1.38
1780	1.82	1.44	1.11	1.29	1.07	1.01	0.96	1.11	1.27	1.09
1790	1.01	0.70	1.16	1.55	1.51	1.21	0.43	0.12	0.37	0.85
1800	1.28	0.90	1.23	1.05	1.24	1.14	0.43	0.94	1.16	0.89
1810	1.41	1.14	1.14	1.09	0.93	0.56	0.63	0.68	1.22	0.82
1820	0.99	1.00	1.21	1.14	1.16	0.95	0.82	1.05	0.69	1.15
1830	0.91	1.17	0.22	0.42	0.57	0.31	0.26	1.21	0.74	1.76
1840	1.96	1.96	1.49	0.95	0.60	0.92	1.65	1.12	1.30	1.55
1850	1.31	1.05	0.58	1.15	1.03	0.68	1.08	0.75	1.20	1.00
1860	1.25	0.99	0.40	0.18	0.92	1.01	1.61	1.15	1.06	1.25
1870	1.07	0.88	0.40	0.15	0.61	1.09	1.01	0.78	0.91	1.12
1880	1.37	0.57	0.36	0.46	1.01	1.32	1.42	1.09	0.82	0.72
1890	0.65	0.51	0.24	0.80	1.42	1.30	1.35	0.89	0.88	1.03
1900	1.32	1.12	0.94	0.67	0.44	0.84	1.40	1.04	0.59	1.33
1910	0.99	0.74	1.23	1.15	0.78	1.27	1.08	1.21	0.69	1.37
1920	0.90	1.49	1.02	0.96	0.52	1.01	1.65	1.58	1.14	0.82
1930	1.04	1.00	1.34	1.24	1.44	0.87	0.44	0.85	0.71	0.96
1940	1.23	0.80	0.81	1.26	0.93	0.94	1.13	0.75	0.95	0.98
1950	1.15	0.85	1.19	1.30	0.78	1.11	0.97	0.72	0.64	0.85
1960	1.07	1.17	1.09	0.69	1.27	1.36	0.97	1.21	0.67	0.96
1970	1.18	1.09	1.07	0.84	1.07	0.56	0.76	1.13	0.90	1.22

The ring width index for each year was derived from 3 radii for the period 1760-1779; 10, 1780-1787; 11, 1788-1789; 14, 1790-1799; 20, 1800-1851; 24, 1852-1857; 25, 1858-1859; 26, 1860-1879; 28, 1880-1979.

Site name *Lake Eyles* Site code *LKE*
Location *Murchison Mountains, Fiordland*
Latitude *45°15'S* Longitude *167°29'E*
Grid reference *NZMS1 S140 546387*
Species collected *Nothofagus menziesii*
No. trees sampled *14* No. cores *27* No. discs *0*
Altitude *950 m* Aspect *NE* Slope *0°*
Date of collection *14 November 1981*
Collectors *D.A.Norton and R.K.Harper*

Site description:

This site is located in the Murchison Mountains to the west of Lake Te Anau. Lake Eyles is located within the Takahe Special Area of Fiordland National Park and a permit must be obtained before visiting the area. Access was by boat to the head of the South Fiord of Lake Te Anau and then on foot up the Chester Burn to Lake Eyles. The site is on the first bench below the lake. Drainage of the undulating surface is variable but at its best is only moderate.

The forest consists of mixed Nothofagus menziesii and N.solandri forming the canopy at about 14-16 m. A diverse subcanopy includes Coprosma species, Olearia ilicifolia, Myrsine divaricata and pole size Nothofagus trees. A variety of ferns are present on the forest floor.

CHRONOLOGY STATISTICS

Chronology code	*LKE636*	Interval (A.D.)	*1676-1980*
No. trees	*10*	No. radii	*19*
Mean ring width (mm)	*1.23*	% absent rings	*0.49*
Autocorrelation	*0.43*		
Mean sensitivity	*0.35*		
Mean standard error	*0.14*		

SAMPLE STATISTICS

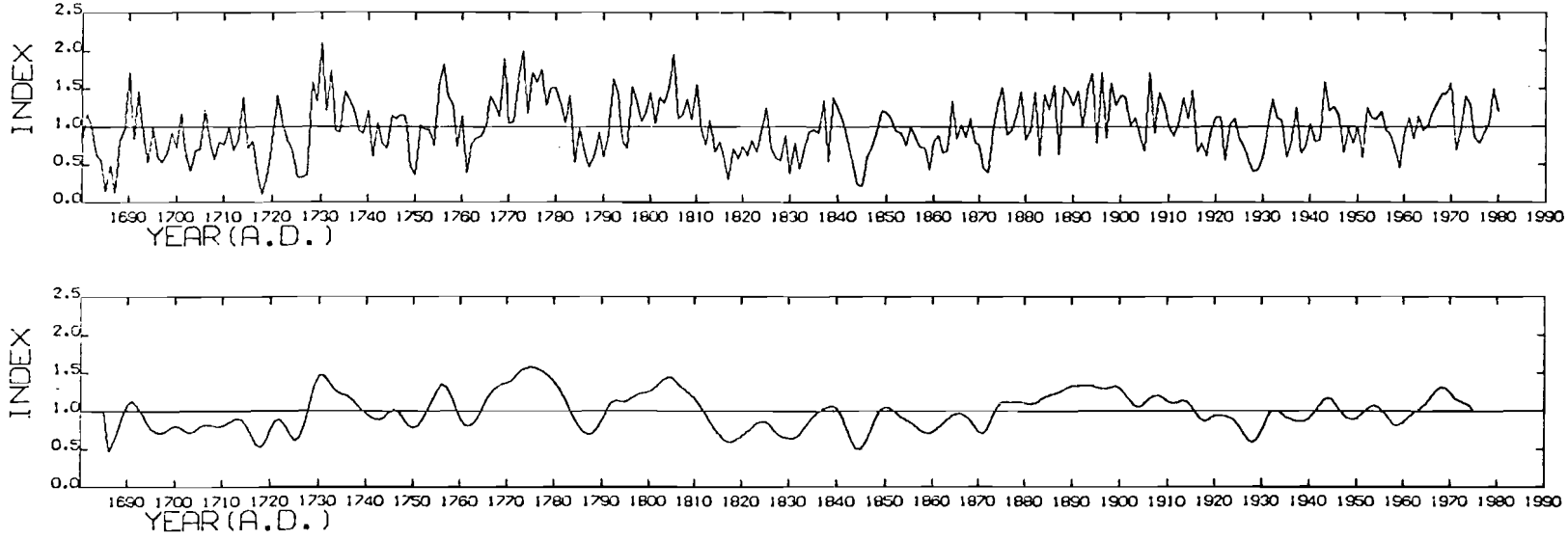
Interval analysed (A.D.) *1861-1980*
No. trees *6* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*30.64*
Differences between trees	*21.83*
Other	*47.53*

Cross-correlation analysis:

Radii within trees	*0.52*
Radii among trees	*0.33*
Between tree means	*0.34*

LKE636 NOTHOFAGUS MENZIESII FIORDLAND 10 TREES, 19 RADII



LKE636 NOTHOFAGUS MENZIESII FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1676							1.82	1.98	1.55	0.72
1680	0.83	1.18	1.00	0.62	0.56	0.13	0.49	0.12	0.81	0.97
1690	1.70	0.83	1.46	0.91	0.52	0.98	0.58	0.53	0.66	0.93
1700	0.72	1.18	0.61	0.41	0.68	0.70	1.22	0.83	0.55	0.79
1710	0.75	0.99	0.68	0.83	1.39	0.71	0.81	0.40	0.09	0.33
1720	0.82	1.41	1.02	0.82	0.66	0.32	0.32	0.35	1.58	1.32
1730	2.10	1.20	1.73	0.93	0.92	1.46	1.35	1.21	0.93	0.91
1740	1.21	0.60	1.04	0.77	0.71	1.15	1.10	1.16	1.11	0.45
1750	0.35	1.02	0.96	0.96	0.75	1.52	1.82	1.38	1.29	0.74
1760	1.13	0.38	0.77	0.85	0.87	0.99	1.39	1.30	1.12	1.89
1770	1.03	1.06	1.61	2.00	1.16	1.71	1.57	1.74	1.27	1.50
1780	1.51	1.31	1.04	1.41	0.53	0.97	0.68	0.46	0.59	0.92
1790	0.59	0.89	1.62	1.41	0.79	0.71	1.52	1.32	1.06	1.19
1800	1.45	1.04	1.38	1.29	1.50	1.95	1.10	1.15	1.36	1.08
1810	1.54	0.95	0.76	1.08	0.66	0.79	0.56	0.29	0.70	0.57
1820	0.74	0.60	0.82	0.66	0.98	1.24	0.71	0.58	0.54	0.88
1830	0.37	0.79	0.43	0.72	0.92	0.95	0.91	1.34	0.53	1.38
1840	1.21	1.06	0.82	0.53	0.21	0.20	0.60	0.72	0.93	1.21
1850	1.17	1.09	0.93	0.91	0.74	0.99	0.86	0.72	0.73	0.42
1860	0.80	0.89	0.64	0.68	1.33	0.83	1.02	0.84	1.11	0.79
1870	0.75	0.44	0.39	0.93	1.30	1.50	0.88	0.95	1.14	1.46
1880	0.82	0.95	1.45	0.60	1.42	1.23	1.54	0.62	1.52	1.43
1890	1.26	1.47	0.99	1.50	1.70	0.78	1.71	0.84	1.57	1.27
1900	1.41	1.38	1.00	1.11	0.88	0.68	1.70	0.91	1.44	1.28
1910	1.01	0.88	1.02	1.36	1.10	1.47	0.65	0.78	0.61	0.96
1920	1.12	1.12	0.54	1.03	1.10	0.83	0.73	0.54	0.39	0.42
1930	0.59	0.97	1.34	1.10	1.07	0.58	0.78	1.24	0.65	0.72
1940	1.03	0.80	0.82	1.58	1.19	1.25	1.13	0.65	0.99	0.77
1950	1.01	0.58	1.25	1.11	1.10	1.19	0.95	0.90	0.73	0.45
1960	0.91	1.12	0.83	1.13	0.94	1.00	1.18	1.30	1.43	1.42
1970	1.57	0.68	0.92	1.39	1.29	0.84	0.77	0.92	1.05	1.50
1980	1.19									

The ring width index for each year was derived from 1 radius for the period 1676-1679; 2, 1680-1699; 3, 1700-1729; 4, 1730-1747; 5, 1748-1797; 6, 1798-1809; 7, 1810-1819; 13, 1820-1826; 14, 1827-1859; 15, 1860-1869; 16, 1870-1876; 17, 1877-1907; 18, 1908-1922; 19, 1923-1980.

Site name	*Lake Pearson*	Site code	*LKP*
Location	*Broken River Basin, Canterbury*		
Latitude	*43°07'S*	Longitude	*171°47'E*
Grid reference	*NZMS1 S66 266078*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*9*	No. cores *12*	No. discs *3*
Altitude	*970 m*	Aspect *NW*	Slope *25°*
Date of collection	*April 1979*		
Collectors	*D.A.Norton*		

Site description:

This site is on the east side of Lake Pearson and can be reached either by boat or by foot around the lake shore. The site is on the property of Craigieburn Sheep Station. Trees were sampled on talus slopes and bluffs high above the lake under Purple Hill. The Nothofagus solandri trees are scattered across the area, being relicts of formerly more extensive forest. The trees, rarely taller than 5 m, are often stunted. Associated species include Pteridium esculentum, Coprosma linariifolia, Cyathodes juniperina and Corokia cotoneaster.

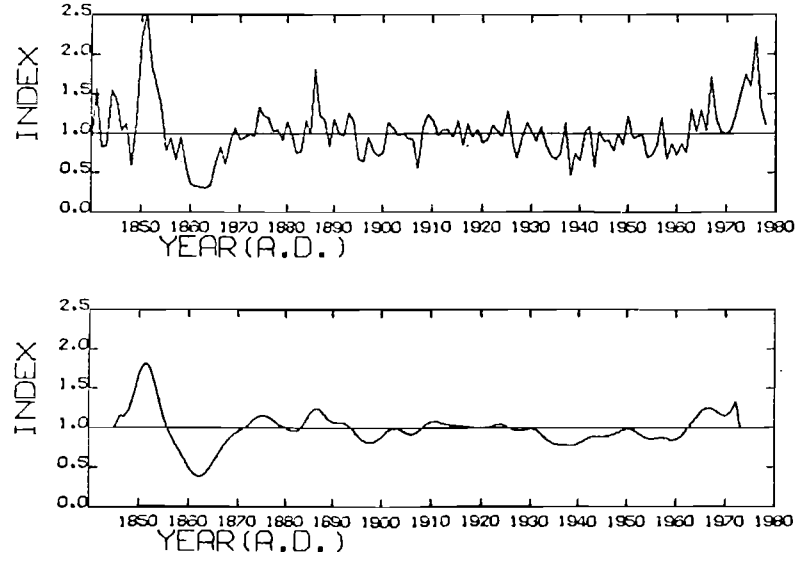
CHRONOLOGY STATISTICS

Chronology code	*LKP609*	Interval (A.D.)	*1833-1978*
No. trees	*6*	No. radii	*11*
Mean ring width (mm)	*1.00*	% absent rings	*0*
Autocorrelation	*0.56*		
Mean sensitivity	*0.25*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

Interval analysed (A.D.)	*1910-1978*
No. trees *5*	No. radii *2*
Analysis of variance (% variance explained):	
Mean chronology	*31.20*
Differences between trees	*29.92*
Other	*38.88*
Cross-correlation analysis:	
Radii within trees	*0.66*
Radii among trees	*0.33*
Between tree means	*0.37*

LKP609 NOTHOFAGUS SOLANDRI CANTERBURY 6 TREES, 11RADII



LKP609 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1833				0.93	0.91	1.67	0.62	0.38	0.38	0.31
1840	0.88	1.55	0.82	0.83	1.54	1.42	1.01	1.12	0.58	1.14
1850	2.21	2.52	1.83	1.60	1.34	0.77	0.94	0.65	0.96	0.58
1860	0.34	0.31	0.31	0.30	0.33	0.62	0.83	0.61	0.89	1.07
1870	0.92	0.94	1.00	0.95	1.33	1.22	1.20	1.02	1.05	0.90
1880	1.14	0.98	0.75	0.77	1.16	0.99	1.81	1.21	1.17	0.83
1890	1.18	0.99	0.98	1.26	1.16	0.68	0.63	0.96	0.77	0.71
1900	0.76	1.13	1.07	0.97	1.00	0.94	0.91	0.56	1.08	1.23
1910	1.17	0.98	1.05	1.04	0.94	1.16	0.85	1.13	0.95	1.04
1920	0.88	0.92	1.09	1.03	0.96	1.29	0.92	0.69	0.95	1.13
1930	1.02	0.90	1.09	0.84	0.71	0.66	0.74	1.13	0.46	0.74
1940	0.64	1.02	1.09	0.56	1.02	0.89	0.91	0.78	1.00	0.84
1950	1.23	0.93	0.96	0.99	0.68	0.73	0.85	1.19	0.67	0.87
1960	0.72	0.87	0.76	1.31	1.02	1.30	1.03	1.71	1.19	1.01
1970	0.99	1.04	1.26	1.52	1.74	1.60	2.22	1.34	1.11	

The ring width index for each year was derived from 1 radius for the period 1833-1865; 2, 1866-1869; 3, 1870-1874; 4, 1875; 5, 1876-1878; 6, 1879-1886; 7, 1887-1896; 8, 1897-1903; 9, 1904; 10, 1905-1909; 11, 1910-1978.

Site name *Mirkwood* Site code *MKW*
Location *Craigieburn Range, Canterbury*
Latitude *43°03'S* Longitude *171°41'E*
Grid reference *NZMS1 S66 169162*
Species collected *Nothofagus menziesii*
No. trees sampled *12* No. cores *24* No. discs *0*
Altitude *1275 m* Aspect *NW* Slope *30°*
Date of collection *4 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Mirkwood is the unofficial name of a large area of forest above the Waimakariri River between McKay Stream and Pylon Gully on the flanks of the Black Range. The site sampled is at the highest altitude reached by this forest and is on a well drained substrate with a shallow soil. The forest canopy is at about 12 m in this monotypic Nothofagus solandri forest. Abundant N.solandri regeneration is present in canopy gaps. Other species present include Coprosma c.f. pseudocuneata, Dracophyllum acerosum and Gaultheria depressa.

CHRONOLOGY STATISTICS

Chronology code	*MKW626*	Interval (A.D.)	*1730-1979*
No. trees	*12*	No. radii	*24*
Mean ring width (mm)	*0.95*	% absent rings	*2.24*
Autocorrelation	*0.56*		
Mean sensitivity	*0.34*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

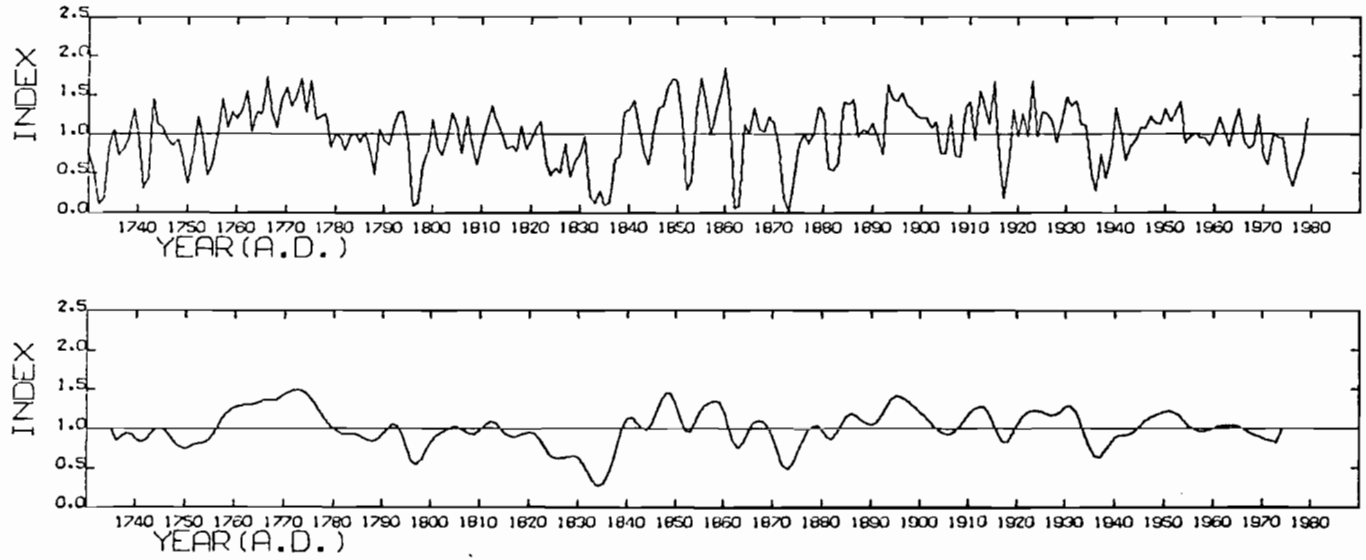
Interval analysed (A.D.) *1880-1070*
No. trees *12* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*36.05*
Differences between trees	*10.08*
Other	*53.87*

Cross-correlation analysis:

Radii within trees	*0.52*
Radii among trees	*0.39*
Between tree means	*0.40*

MKW626 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 24 RADII



MKW626 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1730	0.76	0.53	0.10	0.19	0.84	1.06	0.72	0.80	0.92	1.32
1740	1.02	0.30	0.43	1.45	1.11	1.08	0.92	0.85	0.93	0.68
1750	0.35	0.72	1.22	0.92	0.48	0.61	0.99	1.46	1.07	1.28
1760	1.19	1.32	1.55	1.02	1.29	1.24	1.72	1.28	1.07	1.45
1770	1.60	1.35	1.47	1.71	1.27	1.68	1.18	1.22	1.26	0.83
1780	1.01	0.95	0.78	0.96	1.01	0.89	1.02	0.79	0.47	1.05
1790	0.91	0.85	1.10	1.27	1.29	0.87	0.08	0.11	0.59	0.79
1800	1.19	0.83	0.72	0.96	1.27	1.11	0.75	1.22	0.88	0.59
1810	0.90	1.12	1.35	1.16	1.01	0.80	0.84	0.77	1.10	0.79
1820	0.92	1.07	1.16	0.67	0.46	0.56	0.49	0.87	0.44	0.65
1830	0.74	0.97	0.19	0.11	0.28	0.09	0.13	0.67	0.70	1.26
1840	1.31	1.42	1.08	0.76	0.60	1.02	1.31	1.35	1.60	1.69
1850	1.66	1.16	0.28	0.38	1.31	1.70	1.37	0.98	1.28	1.51
1860	1.85	1.30	0.05	0.08	1.12	1.00	1.33	1.06	1.03	1.22
1870	1.14	0.80	0.17	0.01	0.42	0.85	1.00	0.87	1.01	1.34
1880	1.27	0.55	0.52	0.62	1.40	1.37	1.43	0.96	1.04	1.02
1890	1.13	0.95	0.74	1.61	1.45	1.41	1.52	1.36	1.31	1.21
1900	1.20	1.19	1.07	1.14	0.74	0.74	1.25	0.71	0.69	1.32
1910	1.41	0.90	1.54	1.35	1.12	1.66	0.72	0.17	0.61	1.31
1920	0.95	1.26	0.96	1.69	0.96	1.28	1.26	1.16	0.88	1.17
1930	1.47	1.35	1.42	1.12	1.11	0.49	0.26	0.74	0.42	0.76
1940	1.34	1.02	0.66	0.85	0.92	1.08	1.07	1.21	1.13	1.12
1950	1.32	1.14	1.27	1.41	0.87	0.96	1.01	0.94	0.95	0.84
1960	1.00	1.21	1.04	0.83	1.10	1.31	0.89	0.80	0.86	1.23
1970	0.71	0.59	0.99	0.95	0.95	0.50	0.32	0.54	0.73	1.19

The ring width index for each year was derived from 1 radius for the period 1730-1739; 3, 1740-1752; 4, 1753-1759; 6, 1760-1764; 7, 1765-1775; 8, 1776; 9, 1777-1779; 10, 1780-1781; 11, 1782-1789; 12, 1790-1798; 13, 1799; 14, 1800-1839; 19, 1840-1849; 20, 1850-1879; 24, 1880-1979.

Site name *Mount Bruce* Site code *MTB*
Location *Craigieburn Range, Canterbury*
Latitude *43°03'S* Longitude *171°38'E*
Grid reference *NZMS1 S66 115153*
Species collected *Nothofagus solandri*
No. trees sampled *15* No. cores *13* No. discs *5*
Altitude *1300 m* Aspect *SE* Slope *35°*
Date of collection *March 1979 and 12 January 1981*
Collectors *D.A.Norton, G.Barron and A.E.Moore*

Site description:

Mount Bruce is located close to Lagoon Saddle. Access is by foot from State Highway 73 close to Bealey. Mount Bruce is located in Bealey State Forest Park. The area of forest is on a steep slope in the Broad Stream catchment. Fire has affected forest in the area but the sampled trees are in undisturbed forest. The monotypic Nothofagus solandri forest forms a canopy at about 8 to 10 m and associated species include Podocarpus nivalis and Coprosma species.

CHRONOLOGY STATISTICS

Chronology code	*MTB613*	Interval (A.D.)	*1758-1979*
No. trees	*14*	No. radii	*36*
Mean ring width (mm)	*0.95*	% absent rings	*1.15*
Autocorrelation	*0.57*		
Mean sensitivity	*0.39*		
Mean standard error	*0.09*		

SAMPLE STATISTICS

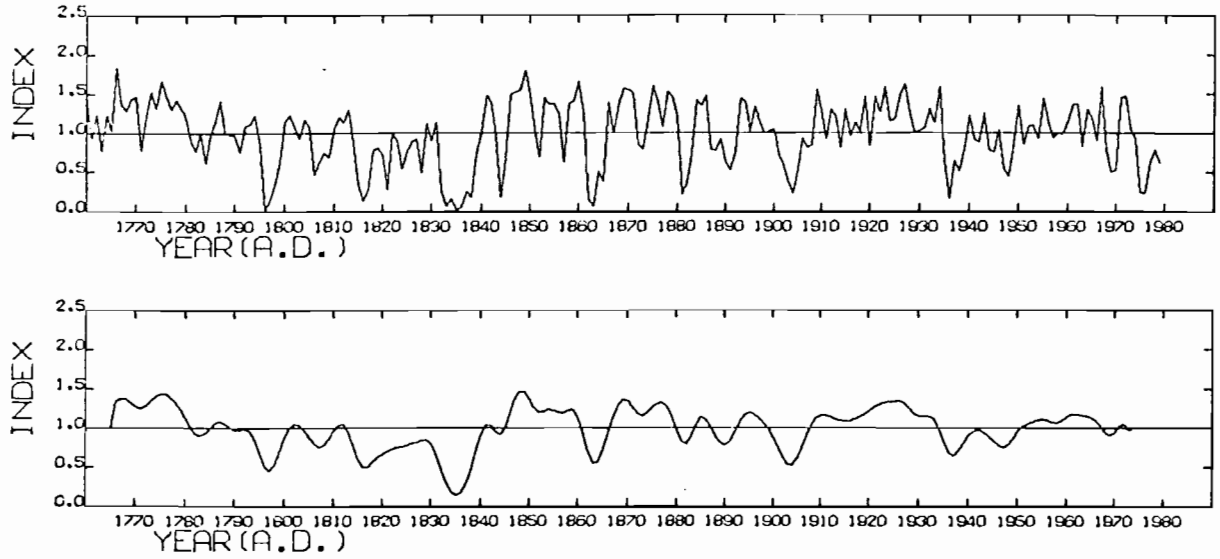
Interval analysed (A.D.) *1890-1976*
No. trees *12* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*46.60*
Differences between trees	*21.34*
Other	*32.06*

Cross-correlation analysis:

Radii within trees	*0.66*
Radii among trees	*0.49*
Between tree means	*0.49*

MTB613 NOTHOFAGUS SOLANDRI CANTERBURY 14 TREES, 36RADII



MTB613 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1758									0.68	1.15
1760	1.37	0.92	1.24	0.76	1.21	1.03	1.83	1.34	1.27	1.44
1770	1.46	0.78	1.21	1.52	1.31	1.66	1.45	1.30	1.42	1.31
1780	1.19	0.89	0.76	1.00	0.61	0.98	1.15	1.41	0.98	0.97
1790	0.96	0.74	1.08	1.11	1.22	0.84	0.01	0.13	0.33	0.62
1800	1.15	1.23	1.08	0.92	1.18	1.08	0.46	0.62	0.74	0.69
1810	1.05	1.19	1.13	1.29	0.88	0.34	0.12	0.27	0.77	0.81
1820	0.72	0.27	0.99	0.91	0.53	0.76	0.88	0.92	0.49	1.12
1830	0.90	1.14	0.24	0.05	0.16	0.00	0.05	0.25	0.17	0.74
1840	1.01	1.47	1.39	0.97	0.16	0.67	1.48	1.52	1.54	1.80
1850	1.48	1.05	0.69	1.45	1.35	1.36	1.24	0.62	1.36	1.40
1860	1.65	1.25	0.15	0.06	0.51	0.37	1.38	0.99	1.35	1.55
1870	1.55	1.49	0.84	0.79	1.17	1.60	1.38	1.07	1.51	1.46
1880	1.20	0.21	0.34	0.74	1.41	1.35	1.46	0.79	0.77	0.92
1890	0.62	0.52	0.74	1.43	1.39	1.02	1.33	1.14	0.99	1.03
1900	1.05	0.72	0.58	0.37	0.22	0.52	0.93	0.81	0.85	1.55
1910	1.27	0.92	1.29	1.21	0.80	1.30	0.95	1.13	1.01	1.45
1920	0.83	1.45	1.26	1.58	1.15	1.17	1.47	1.62	1.25	0.99
1930	1.03	1.06	1.31	1.13	1.59	0.63	0.16	0.65	0.51	0.80
1940	1.22	0.92	0.87	1.24	0.78	0.74	1.03	0.54	0.43	0.85
1950	1.35	0.84	1.09	1.10	0.92	1.43	1.12	0.93	0.99	0.98
1960	1.14	1.36	1.35	0.82	1.30	1.18	0.90	1.58	0.79	0.50
1970	0.52	1.43	1.47	1.06	0.92	0.23	0.22	0.62	0.79	0.60

The ring width index for each year was derived from 1 radius for the period 1758-1759; 2, 1760-1762; 3, 1763-1767; 4, 1768-1769; 5, 1770-1776; 6, 1778-1798; 7, 1799-1818; 8, 1819-1827; 9, 1828; 10, 1829-1839; 16, 1840-1854; 17, 1855-1866; 18, 1867; 19, 1868; 20;1869; 21, 1870; 22, 1871-1875; 23, 1876-1877; 24, 1878; 26, 1879; 32, 1880-1886; 33, 1887-1888; 34, 1889; 35, 1890-1900; 36, 1901-1976; 35, 1977; 34, 1978; 15, 1979.

Site name *Lake Orbell* Site code *OBL*
Location *Murchison Mountains, Fiordland*
Latitude *45°18'S* Longitude *167°41'E*
Grid reference *NZMS1 S140 723348*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *26* No. discs *0*
Altitude *1000 m* Aspect *S* Slope *20°*
Date of collection *3 February 1981, 15 November 1981*
Collectors *D.A.Norton and R.K.Harper*

Site description:

Lake Orbell is located in Takahe Valley at the eastern end of the Murchison Mountains. Takahe Valley is in the Takahe Special Area of Fiordland National Park and a permit must be obtained before visiting the area. Access is by boat to the Te Ana-au caves and then by foot to Takahe Valley. The site is located on the north side of Lake Orbell between the lake edge and the prominent limestone bluffs above the lake. The forest is tall (20 m) and mixed Nothofagus solandri and N.menziesii; only the latter species was sampled. The scrub layer consists mainly of Coprosma pseudocuneata, C.ciliata and C.astonii. Some Hoheria glabrata is also present. The substrate consists of limestone debris and a thin soil. Drainage is moderate.

CHRONOLOGY STATISTICS

Chronology code	*OBL610*	Interval (A.D.)	*1584-1980*
No. trees	*12*	No. radii	*20*
Mean ring width (mm)	*0.94*	% absent rings	*0.34*
Autocorrelation	*0.43*		
Mean sensitivity	*0.31*		
Mean standard error	*0.12*		

SAMPLE STATISTICS

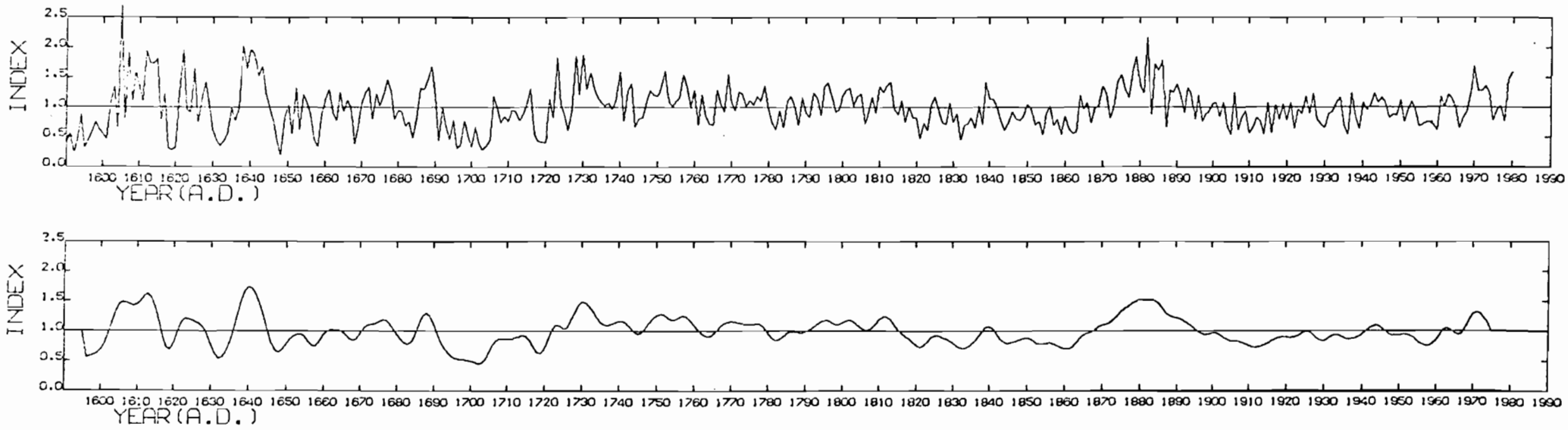
Interval analysed (A.D.) *1863-1979*
No. trees *5* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*33.78*
Differences between trees	*13.38*
Other	*52.84*

Cross-correlation analysis:

Radii within trees	*0.51*
Radii among trees	*0.35*
Between tree means	*0.37*

OBL610 NOTHOFAGUS MENZIESII FIORDLAND 12 TREES, 20 RADII



OBL610 NOTHOFAGUS MENZIESII FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1584					0.61	0.51	0.98	0.83	0.61	0.57
1590	0.39	0.57	0.23	0.44	0.86	0.32	0.44	0.58	0.75	0.61
1600	0.54	0.45	1.07	1.35	0.66	2.69	0.81	1.91	1.11	1.60
1610	1.34	1.10	1.94	1.73	1.74	1.81	0.78	1.22	0.31	0.27
1620	0.31	1.26	1.96	0.96	0.91	1.64	0.75	1.13	1.42	1.06
1630	0.61	0.43	0.35	0.43	0.55	0.99	0.77	0.98	2.01	1.64
1640	1.96	1.88	1.52	1.68	1.24	0.99	0.78	0.43	0.19	0.84
1650	1.03	0.54	1.32	0.62	1.20	1.07	0.88	0.47	0.34	0.90
1660	1.14	1.29	0.91	0.77	1.24	0.93	1.12	0.98	0.38	0.69
1670	1.06	1.24	1.33	0.79	1.22	1.02	1.21	1.46	1.27	0.80
1680	0.95	0.92	0.69	0.76	0.48	0.81	1.32	1.29	1.45	1.68
1690	1.18	0.43	1.00	0.67	0.45	0.78	0.31	0.36	0.77	0.52
1700	0.34	0.67	0.40	0.29	0.35	0.44	1.19	0.99	0.74	0.85
1710	0.76	0.95	0.93	0.77	0.87	1.04	1.30	0.53	0.42	0.41
1720	0.40	1.14	0.82	1.83	1.05	0.87	0.61	0.93	1.86	1.21
1730	1.87	1.30	1.58	1.31	1.17	1.08	1.01	1.06	0.95	1.13
1740	1.60	0.77	1.27	1.40	0.68	0.80	0.82	1.09	1.29	1.20
1750	1.18	1.33	1.61	1.09	1.00	1.09	1.15	1.54	1.35	1.01
1760	1.29	0.69	1.21	0.85	0.71	0.69	1.28	1.05	0.92	1.55
1770	1.08	0.95	1.26	1.21	1.01	1.11	1.03	1.19	1.10	1.36
1780	0.95	0.73	0.62	0.95	0.65	1.10	1.18	1.01	0.69	1.16
1790	0.90	0.83	1.24	1.16	0.85	1.35	1.40	1.18	0.91	0.96
1800	1.18	1.28	1.32	1.03	1.17	1.22	0.72	0.91	1.17	0.89
1810	1.35	1.24	1.36	1.42	0.96	0.87	1.11	0.74	1.00	0.82
1820	0.83	0.47	0.74	0.61	1.04	1.17	0.96	0.74	0.71	1.07
1830	0.74	0.90	0.44	0.69	0.71	0.81	0.65	1.01	0.71	1.42
1840	1.13	1.14	0.98	0.77	0.61	0.75	0.92	0.81	0.77	0.86
1850	1.05	0.97	0.69	0.76	0.53	0.89	1.02	0.68	0.79	0.54
1860	0.85	0.65	0.56	0.57	1.19	0.96	1.07	0.74	0.99	1.01
1870	1.35	1.24	0.81	1.00	1.44	1.53	1.28	1.16	1.57	1.84
1880	1.35	1.23	2.15	0.86	1.72	1.60	1.79	0.66	1.28	1.24
1890	1.38	1.21	0.89	1.32	1.22	0.80	1.19	0.76	0.87	0.91
1900	1.05	1.07	0.83	1.08	0.67	0.53	1.25	0.60	0.83	0.94
1910	0.56	0.65	0.82	0.75	0.54	1.07	0.56	1.03	0.78	1.05
1920	0.78	1.08	0.63	0.95	0.88	1.18	0.89	1.23	0.79	0.70
1930	0.65	0.88	0.92	1.07	1.16	0.68	0.54	1.23	0.82	0.63
1940	1.08	0.94	1.04	1.24	1.07	1.16	1.07	0.81	0.87	0.86
1950	1.12	0.74	0.94	1.09	0.95	0.67	0.70	0.75	0.75	0.70
1960	0.61	1.17	0.99	1.21	1.15	0.99	0.65	0.82	0.92	1.24
1970	1.69	1.28	1.27	1.34	1.25	0.77	0.96	1.02	0.76	1.46
1980	1.59									

The ring width index for each year was derived from 1 radius for the period 1584-1606; 2, 1607-1641; 3, 1642-1659; 4, 1660-1665; 5, 1666-1669; 6, 1670-1700; 7, 1701-1714; 8, 1715-1739; 9, 1740-1751; 10, 1752-1755; 11, 1756; 12, 1757-1766; 13, 1767-1769; 14, 1770-1771; 15, 1772-1788; 16, 1789-1830; 15, 1831-1837; 16, 1838-1849; 8, 1850-1862; 19, 1863-1979; 4, 1980.

Site name *Ribbonwood Creek* Site code *RBW*
Location *Craigieburn Range, Canterbury*
Latitude *43°06'S* Longitude *171°44'E*
Grid reference *NZMS1 S66 209099*
Species collected *Nothofagus solandri*
No. trees sampled *14* No. cores *28* No. discs *0*
Altitude *1350 m* Aspect *SE* Slope *20 -25°*
Date of collection *11 January 1981*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Ribbonwood Creek drains the north side of Mount Mason, at the northern end of the Craigieburn Range, and is located within Craigieburn Forest Park. Access is, however, through Grasmere Sheep Station. The site is located at the upstream margin of forest on the true left-hand side of the stream. Large diameter, multi-stemmed trees form the closed canopy at about 10 m. Only the largest stem per tree was sampled. The forest interior is open with plentiful Nothofagus solandri regeneration. Several subalpine scrub species (e.g. Gaultheria crassa, Phyllocladus alpinus, Podocarpus nivalis) grow within the forest.

CHRONOLOGY STATISTICS

Chronology code	*RBW628*	Interval (A.D.)	*1760-1979*
No. trees	*14*	No. radii	*28*
Mean ring width (mm)	*1.03*	% absent rings	*0.76*
Autocorrelation	*0.44*		
Mean sensitivity	*0.31*		
Mean standard error	*0.08*		

SAMPLE STATISTICS

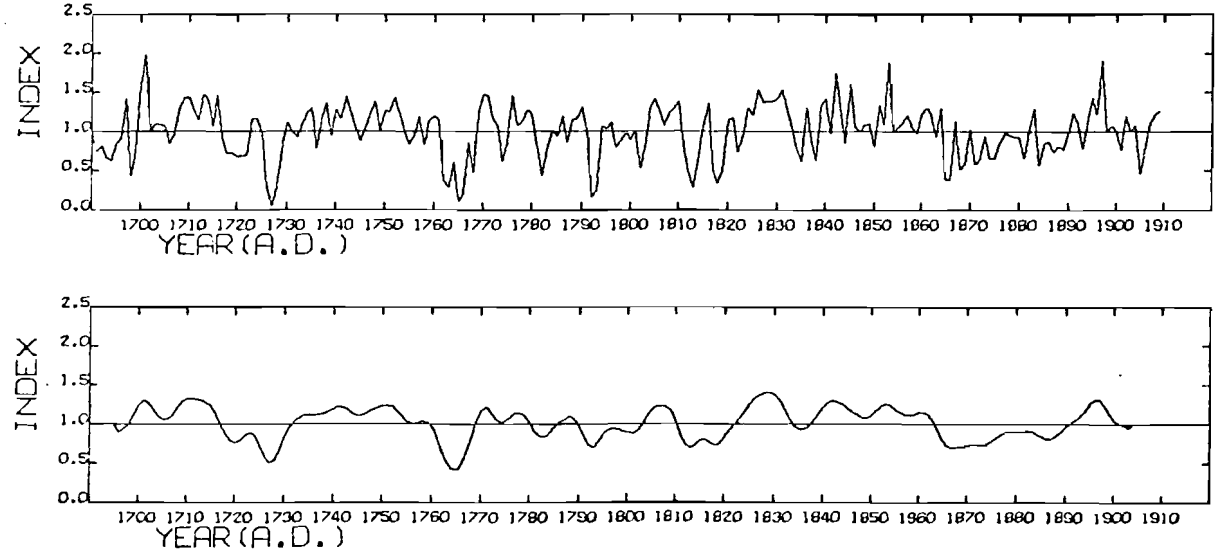
Interval analysed (A.D.) *1860-1979*
No. trees *14* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*38.66*
Differences between trees	*13.01*
Other	*48.33*

Cross-correlation analysis:

Radii within trees	*0.53*
Radii among trees	*0.40*
Between tree means	*0.41*

RBW628 NOTHOFAGUS SOLANDRI CANTERBURY 14 TREES, 28 RADII



RBW628 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1760	0.94	0.72	0.81	0.65	0.63	0.84	0.90	1.42	0.42	0.75
1770	1.60	1.99	1.00	1.09	1.09	1.06	0.83	0.97	1.30	1.44
1780	1.44	1.27	1.13	1.47	1.40	1.05	1.46	0.90	0.71	0.72
1790	0.67	0.68	0.69	1.16	1.15	0.96	0.27	0.05	0.29	0.76
1800	1.11	0.99	0.93	1.10	1.23	1.30	0.77	1.16	1.36	0.93
1810	1.27	1.15	1.44	1.25	1.04	0.87	1.04	1.23	1.39	1.01
1820	1.25	1.25	1.43	1.24	0.98	0.81	0.96	1.18	0.82	1.14
1830	1.20	1.13	0.36	0.28	0.61	0.10	0.22	0.85	0.47	1.21
1840	1.47	1.46	1.16	1.05	0.61	0.87	1.46	1.07	1.12	1.27
1850	1.21	0.81	0.43	0.77	1.00	0.94	1.20	0.86	1.15	1.16
1860	1.30	1.00	0.16	0.23	1.06	1.03	1.11	0.78	0.88	0.97
1870	0.88	1.00	0.52	0.80	1.29	1.41	1.26	1.06	1.23	1.30
1880	1.39	0.81	0.47	0.27	0.62	1.06	1.35	0.50	0.33	0.50
1890	1.15	1.17	0.73	0.95	1.29	1.19	1.53	1.37	1.39	1.38
1900	1.42	1.53	1.26	1.04	0.76	0.61	1.31	0.87	0.62	1.33
1910	1.41	0.95	1.74	1.29	0.84	1.61	1.05	0.99	1.09	1.10
1920	0.80	1.33	1.08	1.88	0.98	1.04	1.12	1.21	1.04	0.95
1930	1.23	1.29	1.22	0.92	1.29	0.38	0.37	1.12	0.50	0.59
1940	1.01	0.58	0.63	0.94	0.64	0.65	0.85	0.97	0.94	0.92
1950	0.92	0.64	1.00	1.29	0.56	0.83	0.87	0.72	0.81	0.76
1960	1.00	1.24	1.09	0.77	1.12	1.44	1.20	1.91	1.00	1.06
1970	0.99	0.75	1.19	0.98	1.08	0.45	0.75	1.10	1.21	1.26

The ring width index for each year was derived from 1 radius for the period 1760-1779; 4, 1780-1789; 5, 1790-1794; 6, 1795-1798; 7, 1799; 9, 1800-1804; 11, 1805-1809; 12, 1810-1812; 13, 1813-1819; 18, 1820-1829; 19, 1830-1831; 20, 1832-1839; 25, 1840-1844; 26, 1845-1859; 28, 1860-1979.

SITE AND COLLECTION INFORMATION

Site name	*Rata Creek*	Site code	*RTA*
Location	*Broken River Basin, Canterbury*		
Latitude	*43°09'S*	Longitude	*171°48'E*
Grid reference	*NZMS1 S66 265027*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*17*	No. cores *30*	No. discs *1*
Altitude	*950 m*	Aspect *N*	Slope *25°*
Date of collection	*27 July 1981*		
Collectors	*P.F.Aston and D.A.Norton*		

Site description:

Rata Creek arises under Broken Hill and drains into Winding Creek. The site is located on the property of Flock Hill Sheep Station. Access is from State Highway 73 by private road to Winding Creek and then on foot to the site. Trees were sampled mainly on talus slopes. Scattered Nothofagus solandri trees within an open canopy at 6 to 8 m occur above a sparse ground flora. Pteridium esculentum is common and the shrubs Corokia cotoneaster, Cyathodes juniperina, Griselinia littoralis and Coprosma linariifolia are also present.

CHRONOLOGY STATISTICS

Chronology code	*RTA606*	Interval (A.D.)	*1787-1980*
No. trees	*12*	No. radii	*21*
Mean ring width (mm)	*1.27*	% absent rings	*0.12*
Autocorrelation	*0.26*		
Mean sensitivity	*0.20*		
Mean standard error	*0.73*		

SAMPLE STATISTICS

Interval analysed (A.D.)	*1881-1970*		
No. trees	*7*	No. radii	*2*

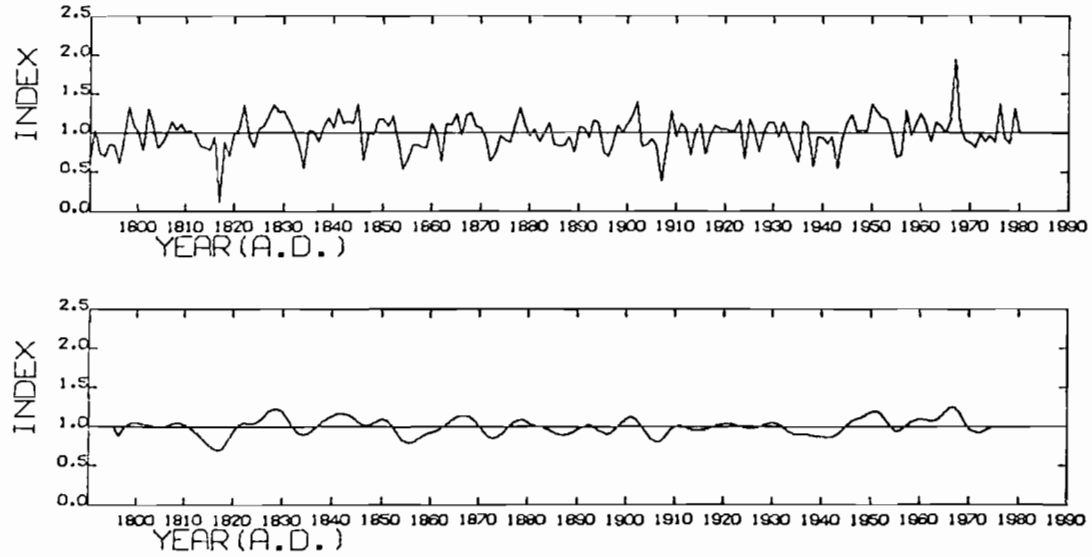
Analysis of variance (% variance explained):

Mean chronology	*22.28*
Differences between trees	*28.46*
Other	*49.26*

Cross-correlation analysis:

Radii within trees	*0.44*
Radii among trees	*0.25*
Between tree means	*0.26*

RTA606 NOTHOFAGUS SOLANDRI CANTERBURY 12 TREES, 21 RADII



RTA606 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1787								0.71	0.90	0.85
1790	0.68	1.04	0.73	0.70	0.86	0.84	0.61	0.94	1.33	1.09
1800	1.01	0.77	1.31	1.10	0.80	0.87	1.00	1.15	1.03	1.11
1810	1.01	1.02	0.98	0.82	0.81	0.77	0.94	0.11	0.88	0.70
1820	0.98	1.05	1.36	0.95	0.80	1.06	1.08	1.21	1.36	1.25
1830	1.27	1.16	1.01	0.84	0.54	1.03	1.00	0.88	1.08	1.19
1840	1.05	1.31	1.12	1.14	1.13	1.37	0.64	1.01	0.96	1.17
1850	1.17	1.09	1.22	0.92	0.54	0.67	0.84	0.85	0.81	0.81
1860	1.12	0.99	0.64	1.12	1.09	1.24	0.97	1.23	1.25	1.07
1870	1.06	0.94	0.63	0.73	0.95	0.90	0.88	1.10	1.32	1.10
1880	0.96	1.04	0.88	1.00	1.13	0.85	0.83	0.83	0.94	0.75
1890	1.07	1.05	0.93	1.16	1.12	0.75	0.70	0.87	1.10	0.99
1900	1.11	1.21	1.39	0.83	0.85	0.92	0.82	0.37	0.80	1.29
1910	0.95	1.12	1.04	0.71	1.01	1.10	0.73	0.96	1.10	1.05
1920	1.04	1.02	1.02	1.16	0.67	1.17	1.02	0.76	1.02	1.13
1930	1.13	0.95	1.14	0.97	0.80	0.61	1.15	1.08	0.57	0.95
1940	0.93	0.86	0.95	0.54	0.93	1.13	1.24	1.02	1.04	1.02
1950	1.38	1.27	1.20	1.17	0.98	0.68	0.71	1.28	0.96	1.10
1960	1.24	1.09	0.89	1.13	1.08	0.99	1.17	1.93	1.06	0.90
1970	0.87	0.81	0.98	0.89	0.96	0.87	1.36	0.92	0.86	1.30
1980	1.00									

The ring width index for each year was derived from 1 radius for the period 1787-1809; 2, 1810; 3, 1811-1817; 4, 1818-1844; 5, 1845-1853; 6, 1854-1861; 7, 1862; 8, 1863; 9, 1864-1866; 10, 1867-1868; 11, 1869-1875; 12, 1876-1877; 13, 1878-1879; 14, 1880; 15, 1881-1884; 16, 1885; 17, 1886-1890; 18, 1891; 19, 1892-1894; 20, 1895-1906; 21, 1907-1971; 19, 1972-1978; 17, 1979; 16, 1980.

Site name *Snowslide Stream* Site code *SSS*
Location *Craigieburn Range, Canterbury*
Latitude *43°03'S* Longitude *171°43'E*
Grid reference *NZMS1 S66 188143*
Species collected *Nothofagus solandri*
No. trees sampled *15* No. cores *30* No. discs *0*
Altitude *1250 m* Aspect *SE* Slope *25°*
Date of collection *15 January 1981*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located on the true left-hand side of the Cass River under Mount Misery in Craigieburn Forest Park. Access is up the spur to the north of Snowslide Stream. Trees were sampled near a prominent saddle where this spur abuts against the rock bluffs of Mount Misery. The forest is of a grouped even-age structure with large mature trees of similar diameter and pole size trees. No seedlings or saplings are present. The forest floor is very sparse; no other species were seen.

CHRONOLOGY STATISTICS

Chronology code	*SSS627*	Interval (A.D.)	*1760-1979*
No. trees	*13*	No. radii	*26*
Mean ring width (mm)	*1.16*	% absent rings	*0.96*
Autocorrelation	*0.55*		
Mean sensitivity	*0.30*		
Mean standard error	*0.08*		

SAMPLE STATISTICS

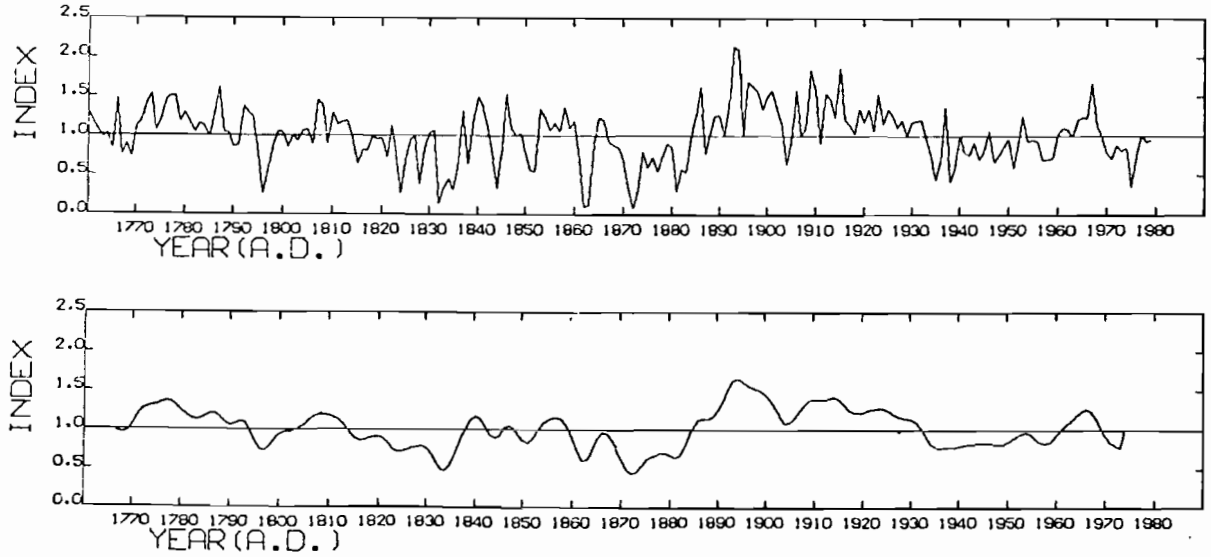
Interval analysed (A.D.) *1840-1979*
No. trees *10* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*45.98*
Differences between trees	*15.78*
Other	*38.24*

Cross-correlation analysis:

Radii within trees	*0.64*
Radii among trees	*0.48*
Between tree means	*0.49*

SSS627 NOTHOFAGUS SOLANDRI CANTERBURY 13 TREES, 26RADII



SSS627 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1760	1.29	1.16	1.06	0.97	1.02	0.83	1.46	0.74	0.88	0.72
1770	1.11	1.17	1.39	1.52	1.06	1.18	1.44	1.49	1.50	1.17
1780	1.28	1.17	1.03	1.15	1.11	0.97	1.27	1.61	1.03	1.03
1790	0.85	0.87	1.37	1.29	1.22	0.76	0.25	0.55	0.86	1.05
1800	1.03	0.84	0.99	0.92	1.06	1.07	0.88	1.44	1.38	0.90
1810	1.28	1.14	1.17	1.18	0.97	0.63	0.81	0.80	0.99	0.95
1820	0.96	0.70	1.12	0.76	0.26	0.65	0.95	0.98	0.36	0.82
1830	1.03	1.06	0.12	0.32	0.45	0.30	0.66	1.30	0.63	1.15
1840	1.49	1.37	1.11	0.75	0.33	0.84	1.52	1.09	0.99	1.02
1850	0.79	0.55	0.53	1.34	1.23	1.06	1.16	1.05	1.35	1.09
1860	1.18	0.68	0.09	0.12	0.89	1.22	1.19	0.92	0.86	0.85
1870	0.69	0.35	0.08	0.30	0.79	0.58	0.72	0.54	0.72	0.89
1880	0.85	0.28	0.57	0.52	0.95	1.25	1.63	0.76	1.02	1.25
1890	1.26	1.00	1.38	2.13	2.08	1.01	1.68	1.63	1.56	1.33
1900	1.49	1.57	1.32	1.13	0.63	0.92	1.57	0.99	1.10	1.84
1910	1.57	0.90	1.53	1.45	1.23	1.86	1.20	1.13	1.02	1.33
1920	1.17	1.34	1.05	1.53	1.15	1.33	1.24	1.10	1.20	1.00
1930	1.18	1.18	1.19	0.94	0.72	0.43	0.67	1.36	0.41	0.59
1940	1.00	0.78	0.74	0.91	0.70	0.80	1.05	0.65	0.75	0.85
1950	0.96	0.58	0.90	1.25	0.92	0.95	0.91	0.68	0.70	0.71
1960	1.01	1.10	1.08	0.99	1.20	1.24	1.22	1.67	1.10	0.98
1970	0.77	0.71	0.87	0.80	0.85	0.34	0.75	1.01	0.92	0.95

The ring width index for each year was derived from 1 radius for the period 1760-1764; 2, 1746; 3, 1747-1748; 4, 1749-1752, 1753-1754; 6, 1755-1758; 7, 1759-1764; 8, 1765; 9, 1766-1789; 10, 1790-1799; 11, 1800-1836; 12, 1837; 13, 1838-1839; 20, 1840-1849; 21, 1850-1876, 22, 1877-1894; 23, 1895-1965; 22, 1966-1979.

Site name	*Takahe Valley*	Site code	*TKV*
Location	*Murchison Mountains, Fiordland*		
Latitude	*45°18'S*	Longitude	*167°41'E*
Grid reference	*NZMS1 S140 718341*		
Species collected	*Nothofagus solandri*		
No. trees sampled	*15*	No. cores *25*	No. discs *0*
Altitude	*1100 m*	Aspect *N*	Slope *20°*
Date of collection	*2 February 1981*		
Collectors	*D.A.Norton*		

Site description:

This site is located in Takahe Valley at the eastern end of the Murchison Mountains, in the Takahe Special Area of Fiordland National Park. Access is by boat to the Te Anau-Au caves and then by foot. The site is located above Lake Orbell on the south side of the valley. Trees were sampled close to the ridge separating Takahe Valley from the Point Burn. The forest is pure Nothofagus solandri with the canopy at about 8-12 m. The undergrowth includes Myrsine divaricata, Phyllocladus alpinus, Archeria traversii and Dracophyllum species. Some Nothofagus menziesii seedlings are present near timberline, but canopy trees are only present at lower altitudes. The parent material is granite.

CHRONOLOGY STATISTICS

Chronology code	*TKV633*	Interval (A.D.)	*1630-1979*
No. trees	*11*	No. radii	*9*
Mean ring width (mm)	*0.85*	% absent rings	*1.37*
Autocorrelation	*0.43*		
Mean sensitivity	*0.30*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

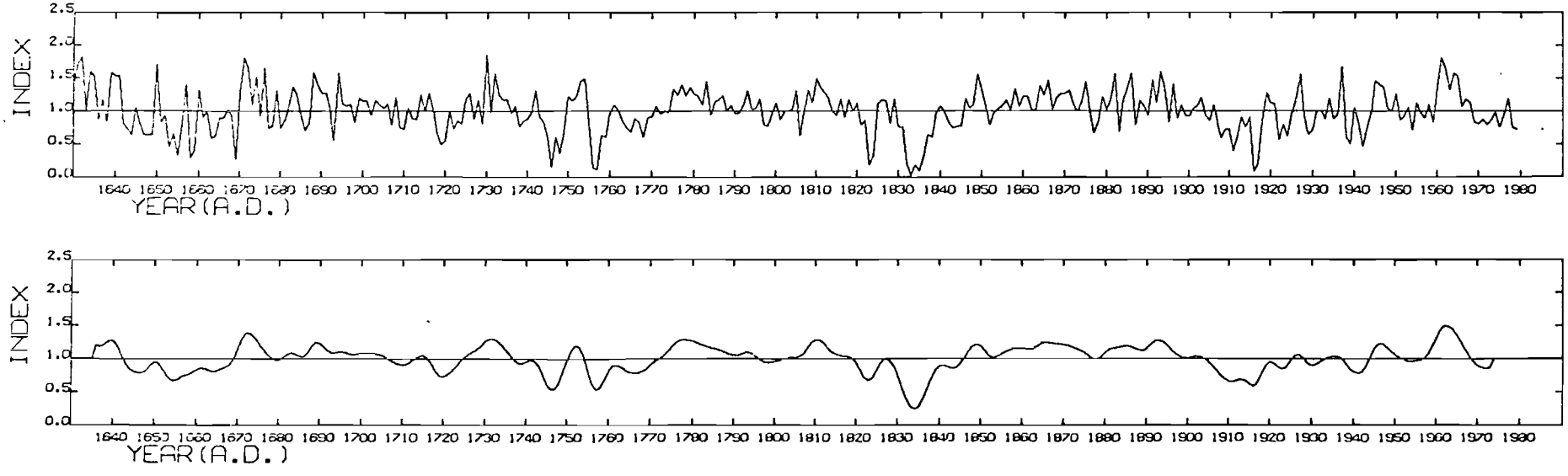
Interval analysed (A.D.) *1840-1979*
No. trees *6* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*37.93*
Differences between trees	*22.17*
Other	*39.90*

Cross-correlation analysis:

Radii within trees	*0.62*
Radii among trees	*0.39*
Between tree means	*0.41*

TKV633 NOTHOFAGUS SOLANDRI FIORDLAND 11 TREES, 19 RADII



TKV633 NOTHOFAGUS SOLANDRI FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1630	1.42	1.73	1.82	1.01	1.60	1.50	0.87	1.17	0.84	1.58
1640	1.52	1.54	0.79	0.73	0.63	1.04	0.81	0.63	0.63	0.65
1650	1.71	0.82	0.93	0.44	0.66	0.31	0.79	1.39	0.28	0.39
1660	1.32	0.90	1.00	0.58	0.62	0.90	0.90	1.02	0.92	0.26
1670	1.29	1.81	1.64	1.08	1.54	0.91	1.66	0.73	0.77	1.31
1680	0.73	0.85	1.07	1.37	1.24	0.92	0.70	0.81	1.58	1.39
1690	1.26	1.27	1.03	0.54	1.57	1.10	1.07	1.10	0.82	1.19
1700	1.15	1.14	0.93	1.16	1.08	1.04	1.10	0.78	1.20	0.74
1710	0.72	1.05	0.87	0.87	1.24	0.98	1.27	1.01	0.65	0.48
1720	0.55	1.00	0.72	0.86	0.79	1.17	1.28	0.87	1.18	0.81
1730	1.85	0.97	1.57	1.23	1.16	1.18	0.96	1.07	0.76	0.85
1740	0.89	0.97	1.31	0.90	0.82	0.60	0.14	0.61	0.34	0.68
1750	1.22	1.15	1.22	1.45	1.49	0.80	0.12	0.11	0.63	0.59
1760	0.97	1.08	1.01	0.84	0.73	0.67	0.88	0.82	0.59	0.89
1770	0.90	1.08	0.95	1.00	0.97	1.33	1.24	1.40	1.22	1.35
1780	1.25	1.23	1.08	1.44	0.94	1.14	1.17	1.23	1.00	1.08
1790	0.95	0.96	1.09	1.30	1.02	1.04	1.18	0.79	0.76	0.96
1800	1.12	0.85	1.00	0.98	1.03	1.31	0.62	1.00	1.32	1.12
1810	1.49	1.34	1.27	1.19	0.98	0.92	1.18	0.90	1.17	0.98
1820	1.12	0.79	0.86	0.17	0.32	1.11	1.17	1.14	0.80	1.18
1830	0.74	0.76	0.20	0.02	0.18	0.08	0.31	0.64	0.59	1.00
1840	1.08	0.97	0.82	0.73	0.77	0.77	1.19	1.03	1.10	1.56
1850	1.32	1.06	0.78	0.98	1.03	1.09	1.16	1.01	1.34	1.06
1860	1.22	1.22	1.01	1.02	1.38	1.24	1.46	1.02	1.19	1.25
1870	1.25	1.30	1.11	0.97	1.14	1.44	0.99	0.65	0.84	1.21
1880	1.02	1.17	1.58	0.68	1.18	1.35	1.57	0.78	1.16	1.07
1890	0.92	1.47	1.13	1.60	1.34	0.82	1.41	0.88	1.08	0.91
1900	0.92	1.03	1.09	1.19	0.91	0.85	1.08	0.84	0.58	0.72
1910	0.72	0.39	0.60	0.91	0.74	0.91	0.08	0.19	0.85	1.28
1920	1.11	1.10	0.56	0.80	0.61	0.96	1.18	1.56	0.92	0.63
1930	0.72	1.00	1.01	0.88	1.20	0.88	0.96	1.66	0.60	0.50
1940	1.04	0.81	0.46	0.73	0.98	1.46	1.40	1.34	1.02	0.99
1950	1.25	0.85	0.93	1.06	0.71	1.12	0.96	0.88	1.10	0.82
1960	1.36	1.81	1.64	1.31	1.57	1.51	1.06	1.17	1.11	0.82
1970	0.80	0.87	0.78	0.86	0.97	0.75	0.95	1.18	0.75	0.71

The ring width index for each year was derived from 1 radius for the period 1630-1659; 2, 1660-1679; 4, 1680-1719; 5, 1720-1739; 7, 1740-1749; 8, 1750-1759; 11, 1760-1779; 12, 1780-1799; 14, 1800-1810; 15, 1811-1819; 16, 1820-1839; 19, 1840-1940; 18, 1941-1977; 17, 1978-1979.

Site name *Tarkus Knob* Site code *TRK*
Location *Cropp River, Westland*
Latitude *43°05'S* Longitude *170°58'E*
Grid reference *NZMS1 S64 523117*
Species collected *Libocedrus bidwillii*
No. trees sampled *80* No. cores *127* No. discs *0*
Altitude *a. 900m, b. 950m* Aspect *SW* Slope *20-40°*
Date of collection *January 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located in the Cropp River catchment, a tributary of the Whitcombe and Hokitika Rivers. Access was by helicopter; foot access from the Hokitika River road end (35 km south of Hokitika township) takes 2 days. The site consists of two subsites.

The Tarkus Knob (unofficial name) subsite is located opposite the New Zealand Forest Service Cropp hut on the true left-hand side of Cropp River. The site is located on the steep slopes above the river flats. The forest is dominated by Olearia colensoi, O. lacunosa, Dracophyllum longifolium, Coprosma pseudocuneata with emergent Dracophyllum traversii and Libocedrus bidwillii.

The Danger Gully subsite is on the true right-hand side of Danger Gully about 0.5 km up the Cropp River from Tarkus Knob. The area sampled is on the northeast side of the spur separating the Cropp River and Danger Gully. The closed canopy at 2-3 m is dominated by Archeria traversii, Dracophyllum longifolium and D. traversii with Libocedrus bidwillii emergent above this.

CHRONOLOGY STATISTICS

Chronology code	*TRK602*	Interval (A.D.)	*1526-1978*
No. trees	*20*	No. radii	*27*
Mean ring width (mm)	*0.52*	% absent rings	*0.24*
Autocorrelation	*0.58*		
Mean sensitivity	*0.17*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

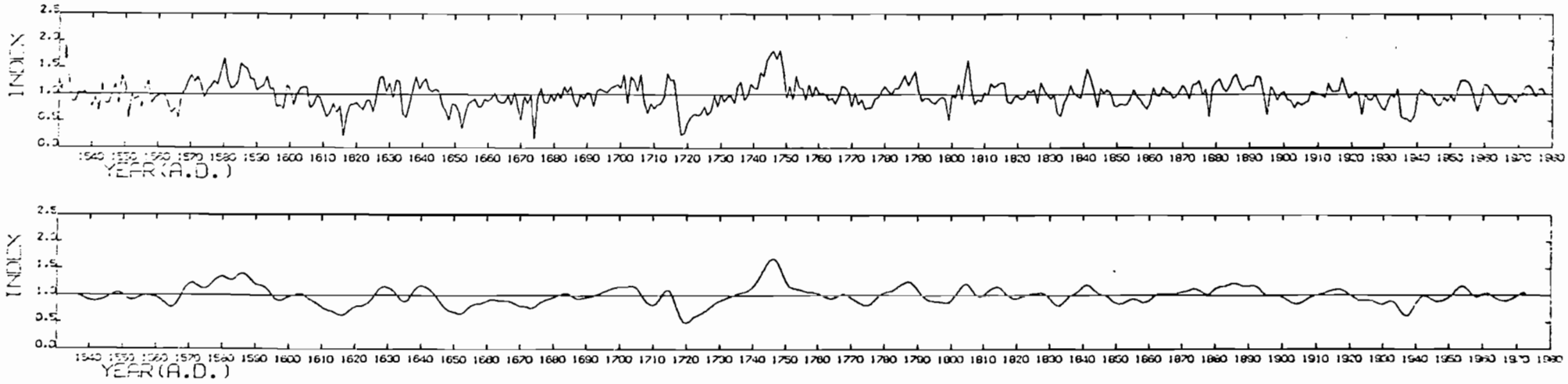
Interval analysed (A.D.) *1897-1964*
No. trees *6* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*17.19*
Differences between trees	*17.18*
Other	*65.63*

Cross-correlation analysis:

Radii within trees	*0.35*
Radii among trees	*0.18*
Between tree means	*0.20*

TRK602 LIBOCEDRUS BIDWILLII WESTLAND 20 TREES, 27 RADII



TRK602 LIBOCEDRUS BIDWILLII WESTLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1526							0.77	0.82	1.30	0.67
1530	1.28	1.06	1.89	1.33	0.86	0.86	1.04	1.00	1.06	0.92
1540	0.76	0.94	0.67	1.20	0.82	0.81	1.02	1.19	0.81	1.34
1550	1.21	0.53	1.00	0.88	0.95	0.75	1.11	1.24	0.82	0.92
1560	0.97	1.00	0.99	0.83	0.64	0.73	0.54	0.99	1.06	1.23
1570	1.36	1.22	1.32	1.17	0.93	1.08	1.15	1.24	1.17	1.43
1580	1.68	1.26	1.11	1.14	1.23	1.57	1.51	1.47	1.29	1.27
1590	1.07	1.13	1.16	1.33	1.09	1.10	0.76	0.78	0.72	1.16
1600	1.09	0.80	0.99	1.12	1.12	1.15	0.73	0.80	0.97	0.94
1610	0.75	0.57	0.66	0.84	0.66	0.78	0.23	0.61	0.81	0.81
1620	0.85	0.76	0.71	0.88	0.88	0.67	0.98	1.31	1.34	1.05
1630	1.21	0.93	1.25	1.25	0.62	0.56	0.83	1.07	1.34	1.09
1640	1.22	1.28	1.09	1.05	1.10	1.05	0.79	0.69	0.51	0.82
1650	0.81	0.68	0.36	0.65	0.84	0.87	0.93	0.77	0.77	0.92
1660	0.87	0.94	1.04	0.87	0.85	0.84	0.98	0.81	1.05	0.78
1670	0.52	0.97	0.82	0.99	0.17	0.91	1.12	0.85	0.84	1.01
1680	0.87	1.04	0.92	1.15	1.03	1.16	0.88	0.77	0.99	0.91
1690	1.03	1.02	0.77	1.07	1.10	1.06	1.04	1.12	1.14	1.18
1700	1.11	1.37	0.83	1.33	1.25	1.06	1.37	0.88	0.65	0.84
1710	0.73	0.81	0.82	0.96	1.40	1.26	1.26	0.75	0.23	0.27
1720	0.47	0.57	0.64	0.60	0.63	0.76	0.61	0.69	0.98	0.77
1730	1.02	0.86	0.96	0.97	0.83	1.16	1.23	0.89	0.97	1.20
1740	1.12	1.09	1.41	1.33	1.64	1.74	1.83	1.65	1.84	1.46
1750	0.94	1.15	0.91	1.35	1.12	1.12	0.89	1.19	0.95	1.14
1760	1.02	1.02	1.00	0.89	0.93	0.82	0.93	1.16	1.11	1.05
1770	0.78	1.03	0.81	0.90	0.72	0.74	0.74	0.93	0.94	1.07
1780	1.14	1.07	0.99	1.11	1.11	1.22	1.36	1.17	1.29	1.43
1790	1.07	0.87	0.93	0.93	0.85	0.82	0.92	0.95	0.91	0.51
1800	1.01	0.93	1.19	0.92	1.34	1.65	1.12	0.82	0.91	0.88
1810	1.05	0.98	1.21	1.13	1.18	1.22	1.22	0.85	0.84	0.95
1820	0.96	0.90	0.94	1.07	1.03	1.09	0.83	1.22	1.09	1.00
1830	0.91	1.00	0.63	0.59	0.85	0.96	1.18	1.01	0.97	0.92
1840	1.20	1.47	1.30	1.08	0.76	1.11	1.02	1.08	1.04	0.78
1850	0.77	0.82	0.81	0.81	0.93	1.09	0.95	0.90	0.79	0.71
1860	0.84	1.13	0.97	0.98	1.13	1.05	1.05	0.93	0.97	1.05
1870	1.17	1.07	0.90	1.18	1.18	1.25	0.98	1.10	0.58	1.14
1880	1.24	1.30	1.14	1.04	1.15	1.32	1.37	1.18	1.07	1.15
1890	1.15	1.14	1.34	1.31	1.01	0.61	1.15	1.06	0.89	1.02
1900	1.06	0.90	0.89	0.74	0.86	0.79	0.85	0.88	1.06	1.03
1910	1.00	0.99	0.94	1.21	1.05	1.06	1.06	1.31	1.11	0.93
1920	0.99	1.05	0.98	0.61	1.01	0.90	0.89	1.00	0.87	0.74
1930	0.69	0.87	1.01	0.93	1.11	0.59	0.53	0.53	0.47	0.59
1940	0.99	1.09	1.03	1.01	0.99	0.87	0.80	0.81	0.96	0.86
1950	1.00	0.86	1.07	1.26	1.28	1.23	1.13	0.92	0.68	0.89
1960	1.20	1.16	1.07	0.97	0.83	0.82	0.83	0.96	0.96	0.84
1970	0.99	0.99	1.14	1.18	1.08	0.95	1.09	1.11	0.99	

The ring width index for each year was derived from 1 radius for the period 1526-1542; 2, 1543-1556; 3, 1557-1568; 4, 1569-1663; 5, 1664-1678; 6, 1679-1688; 7, 1689-1712; 8, 1713-1745; 9, 1746-1769; 10, 1770-1773; 11, 1774-1777; 12, 1778-1779; 11, 1780-1782; 12, 1783-1785; 13, 1786-1794; 14, 1795-1797; 15, 1798-1805; 16, 1806-1828; 17, 1829-1836; 18, 1837-1844; 20, 1845-1847; 21, 1848-1857; 22, 1858-1864; 23 1865-1875; 24, 1876; 25, 1877-1896; 26, 1897-1957; 25, 1958-1965; 24, 1966-1970; 23, 1971-1978.

Site name *Takahe Stream* Site code *TST*
Location *Murchison Mountains, Fiordland*
Latitude *45°17'S* Longitude *167°39'E*
Grid reference *NZMS1 S140 683365*
Species collected *Nothofagus solandri*
No. trees sampled *15* No. cores *26* No. discs *0*
Altitude *1000 m* Aspect *NE* Slope *10 -20°*
Date of collection *1 February 1981*
Collectors *D.A.Norton*

Site description:

The Takahe Stream and Upper Takahe Valley sites are located in the same forest stand in upper Takahe Valley, eastern Murchison Mountains. Takahe Valley is in the Takahe Special Area of Fiordland N.P. and a permit is required to visit the area. Access is by helicopter, or by boat to the Te Ana-au caves and then on foot. The site is on the south side of the valley near the upstream limit of forest.

Mixed Nothofagus menziesii - N.solandri forest occurs on the mid slopes while pure N.solandri forest occurs above and below this. Most of the sampled trees were in the mixed forest zone. A tall canopy is present at about 16 to 20 m. Regeneration of both Nothofagus species is abundant. Coprosma ciliata, C.astonii and C.pseudocuneata are the main shrub species and together with Nothofagus regeneration form dense thickets. Other species present include Hoheria glabrata, Phyllocladus alpinus, Pseudopanax colensoi and Dracophyllum longifolium. Various ferns and Astelia nervosa are common on the forest floor.

CHRONOLOGY STATISTICS

Chronology code	*TST634*	Interval (A.D.)	*1840-1979*
No. trees	*11*	No. radii	*19*
Mean ring width (mm)	*1.35*	% absent rings	*1.24*
Autocorrelation	*0.56*		
Mean sensitivity	*0.36*		
Mean standard error	*0.08*		

SAMPLE STATISTICS

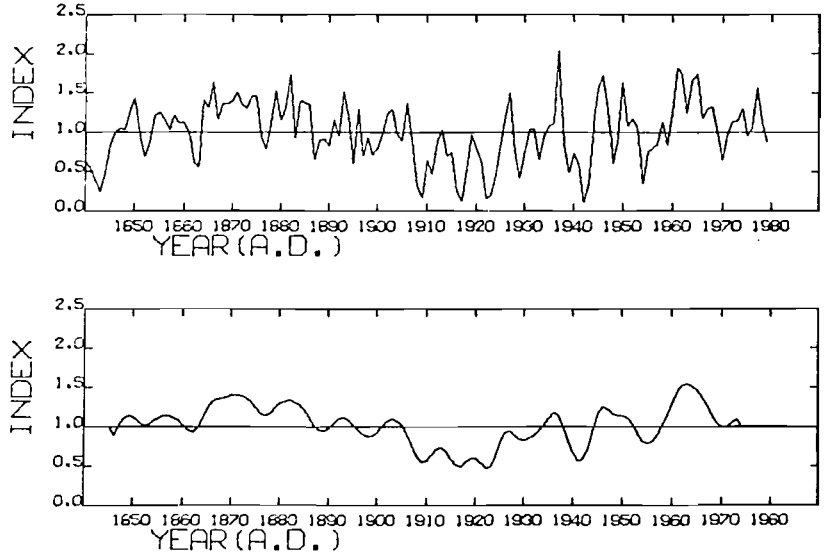
Interval analysed (A.D.) *1850-1978*
No. trees *7* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*52.47*
Differences between trees	*11.41*
Other	*36.12*

Cross-correlation analysis:

Radii within trees	*0.67*
Radii among trees	*0.54*
Between tree means	*0.55*

TST634 NOTHOFAGUS SOLANDRI FIORDLAND 11 TREES, 19 RADII



TST634 NOTHOFAGUS SOLANDRI FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1840	0.61	0.54	0.38	0.23	0.48	0.84	1.00	1.04	1.02	1.28
1850	1.43	0.99	0.68	0.87	1.21	1.25	1.17	1.02	1.21	1.10
1860	1.12	0.98	0.61	0.54	1.41	1.30	1.63	1.16	1.36	1.36
1870	1.40	1.51	1.35	1.30	1.46	1.46	0.95	0.78	1.10	1.53
1880	1.15	1.31	1.74	0.92	1.39	1.38	1.33	0.65	0.89	0.90
1890	0.82	1.16	0.94	1.50	1.19	0.60	1.30	0.70	0.93	0.71
1900	0.79	0.98	1.23	1.30	0.97	0.89	1.37	0.91	0.32	0.16
1910	0.65	0.48	0.88	1.03	0.69	0.75	0.23	0.11	0.53	0.97
1920	0.79	0.61	0.14	0.20	0.46	0.84	1.20	1.49	0.75	0.40
1930	0.75	1.03	1.03	0.64	0.96	1.07	1.13	2.04	0.85	0.48
1940	0.73	0.58	0.10	0.33	1.08	1.55	1.72	1.30	0.60	0.93
1950	1.63	1.07	1.17	1.03	0.33	0.75	0.80	0.84	1.13	0.83
1960	1.25	1.82	1.74	1.23	1.66	1.74	1.17	1.28	1.32	0.98
1970	0.63	0.96	1.13	1.14	1.30	0.95	1.05	1.56	1.13	0.87

The ring width index for each year was derived from 17 radii for the period 1840-1849; 18, 1850-1880; 19, 1881-1913; 18, 1914-1933; 17, 1934-1978; 16, 1979.

Site name *Upper Hollyford Valley* Site code *UHV*
Location *Hollyford Valley, Fiordland*
Latitude *44°46'S* Longitude *168°00'E*
Grid reference *NZMS1 S122 976996*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *18* No. discs *5*
Altitude *950 m* Aspect *S* Slope *0-20°*
Date of collection *18 November 1981*
Collectors *D.A.Norton and R.K.Harper*

Site description:

This site is located adjacent to the Te Anau-Milford Sound road not far from the eastern entrance to Homer Tunnel. Discs were obtained from avalanche felled trees in the runout zone of the Raspberry Patch avalanche track (see Fitzharris and Owens 1980, p.53). The trees had been felled during the 1980 winter. Cored trees were located in a patch of forest undisturbed by avalanches between the Talbot avalanche track and Homer Hut to the north of the road. The area is flat and the soils skeletal. Nothofagus menziesii is the only canopy tree. The dense subcanopy scrub includes Pseudopanax colensoi, Archeria traversii, Hoheria glabrata, Senecio benettii and Olearia ilicifolia.

CHRONOLOGY STATISTICS

Chronology code	*UHV635*	Interval (A.D.)	*1710-1980*
No. trees	*9*	No. radii	*18*
Mean ring width (mm)	*1.08*	% absent rings	*0.19*
Autocorrelation	*0.50*		
Mean sensitivity	*0.24*		
Mean standard error	*0.13*		

SAMPLE STATISTICS

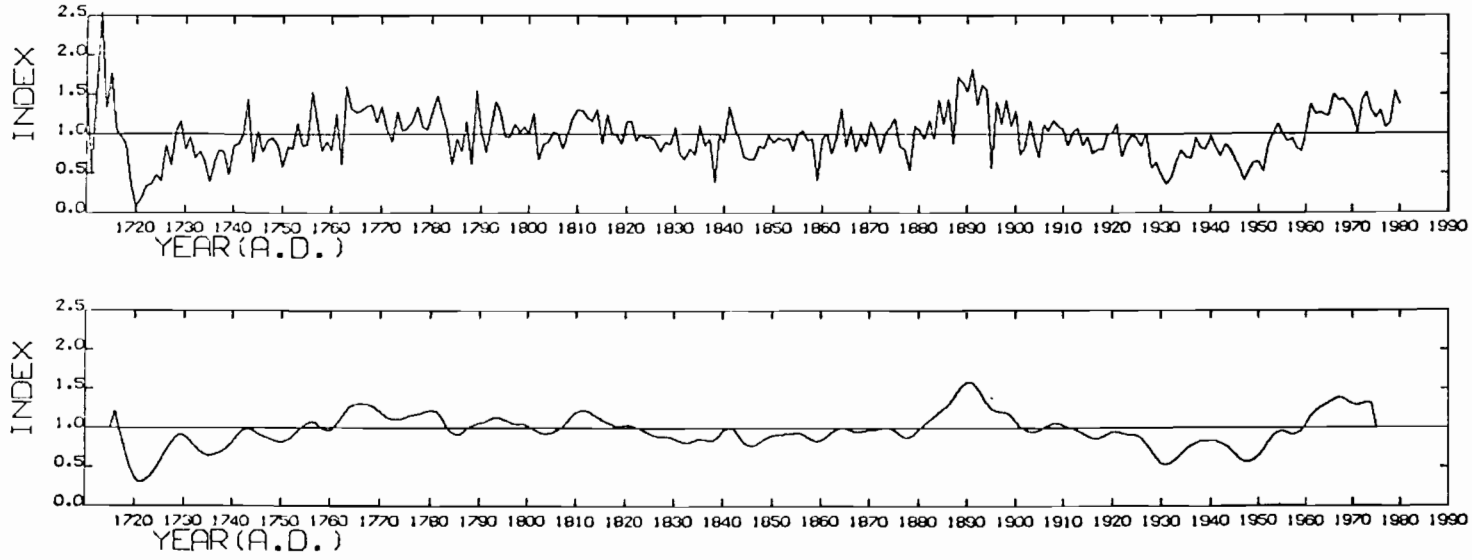
Interval analysed (A.D.) *1882-1980*
No. trees *7* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*37.61*
Differences between trees	*16.61*
Other	*45.78*

Cross-correlation analysis:

Radii within trees	*0.53*
Radii among trees	*0.39*
Between tree means	*0.40*

UHV635 NOTHOFAGUS MENZIESII FIORDLAND 9 TREES, 18 RADII



UHV635 NOTHOFAGUS MENZIESII FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1710	1.66	0.52	1.47	2.54	1.34	1.77	1.06	0.96	0.86	0.35
1720	0.07	0.17	0.33	0.36	0.47	0.39	0.85	0.60	1.02	1.16
1730	0.79	0.96	0.68	0.77	0.64	0.38	0.64	0.80	0.77	0.47
1740	0.84	0.87	1.00	1.45	0.64	1.04	0.76	0.92	0.94	0.86
1750	0.57	0.84	0.81	1.14	0.84	0.86	1.54	1.16	0.78	0.89
1760	0.79	1.26	0.60	1.61	1.32	1.27	1.29	1.35	1.37	1.14
1770	1.35	1.06	0.90	1.29	1.03	1.07	1.15	1.35	1.10	1.05
1780	1.27	1.48	1.26	1.06	0.60	0.94	0.77	1.16	0.60	1.55
1790	1.03	0.76	1.05	1.41	1.25	0.96	0.95	1.12	1.01	1.08
1800	1.00	1.26	0.67	0.86	0.90	1.02	1.00	0.81	1.00	1.21
1810	1.30	1.29	1.21	1.15	1.31	0.87	1.25	1.00	0.98	0.87
1820	1.16	1.16	0.91	0.99	0.95	0.96	0.91	0.77	0.90	0.86
1830	1.09	0.73	0.67	0.80	0.73	1.11	0.85	0.93	0.39	0.98
1840	0.88	1.34	1.07	0.93	0.69	0.67	0.67	0.84	0.81	0.96
1850	0.88	0.95	0.91	0.94	0.79	1.00	1.04	0.90	0.93	0.41
1860	0.94	1.00	0.74	0.94	1.31	0.84	1.09	0.77	0.97	0.84
1870	1.16	1.02	0.75	1.01	1.09	1.20	0.83	0.81	0.53	1.10
1880	1.04	0.94	1.17	0.93	1.43	1.11	1.45	0.88	1.73	1.66
1890	1.53	1.82	1.37	1.62	1.56	0.56	1.41	1.12	1.43	1.10
1900	1.30	0.74	0.82	1.17	0.92	0.70	1.12	1.03	1.17	1.09
1910	1.05	0.85	1.02	1.07	0.84	0.96	0.75	0.79	0.79	1.00
1920	1.01	1.12	0.71	0.90	0.97	0.94	0.83	1.01	0.56	0.63
1930	0.47	0.36	0.44	0.64	0.78	0.69	0.68	0.94	0.81	0.79
1940	0.97	0.80	0.71	0.86	0.78	0.65	0.56	0.40	0.53	0.64
1950	0.64	0.51	0.85	0.99	1.12	1.00	0.89	0.93	0.80	0.78
1960	1.02	1.37	1.24	1.26	1.24	1.22	1.50	1.43	1.43	1.36
1970	1.28	0.98	1.42	1.52	1.29	1.20	1.29	1.07	1.13	1.53
1980	1.37									

The ring width index for each year was derived from 2 radii for the period 1710-1749; 3, 1750-1789; 4, 1790-1799; 5, 1800-1819; 7, 1820-1821; 8, 1822-1834; 9, 1835-1839; 10, 1840-1846; 11, 1847-1849; 12, 1850; 11, 1847-1849; 12, 1850; 11, 1851-1879; 15, 1880-1881; 16, 1882-1889; 17, 1890-1980.

Site name *Upper Takahe Valley* Site code *UTV*
Location *Murchison Mountains, Fiordland*
Latitude *45°17'S* Longitude *167°39'E*
Grid reference *NZMS1 S140 683365*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *30* No. discs *0*
Altitude *1000 m* Aspect *NE* Slope *10 -20°*
Date of collection *1 February 1981*
Collectors *D.A.Norton*

Site description:

The Takahe Stream and Upper Takahe Valley sites are located in the same forest stand in upper Takahe Valley, eastern Murchison Mountains. Takahe Valley is in the Takahe Special Area of Fiordland N.P. and a permit is required to visit the area. Access is by helicopter, or by boat to the Te Ana-au caves and then on foot. The site is on the south side of the valley near the upstream limit of forest.

Mixed Nothofagus menziesii - N.solandri forest occurs on the mid slopes while pure N.solandri forest occurs above and below this. Most of the sampled trees were in the mixed forest zone. A tall conopy is present at about 16 to 20 m. Regeneration of both Nothofagus species is abundant. Coprosma ciliata, C.astonii and C.pseudocuneata are the main shrub species and together with Nothofagus regeneration form dense thickets. Other species present include Hoheria glabrata, Phyllocladus alpinus, Pseudopanax colensoi and Dracophyllum longifolium. Various ferns and Astelia nervosa are common on the forest floor.

CHRONOLOGY STATISTICS

Chronology code	*UTV611*	Interval (A.D.)	*1622-1979*
No. trees	*10*	No. radii	*16*
Mean ring width (mm)	*1.51*	% absent rings	*0.33*
Autocorrelation	*0.56*		
Mean sensitivity	*0.30*		
Mean standard error	*0.12*		

SAMPLE STATISTICS

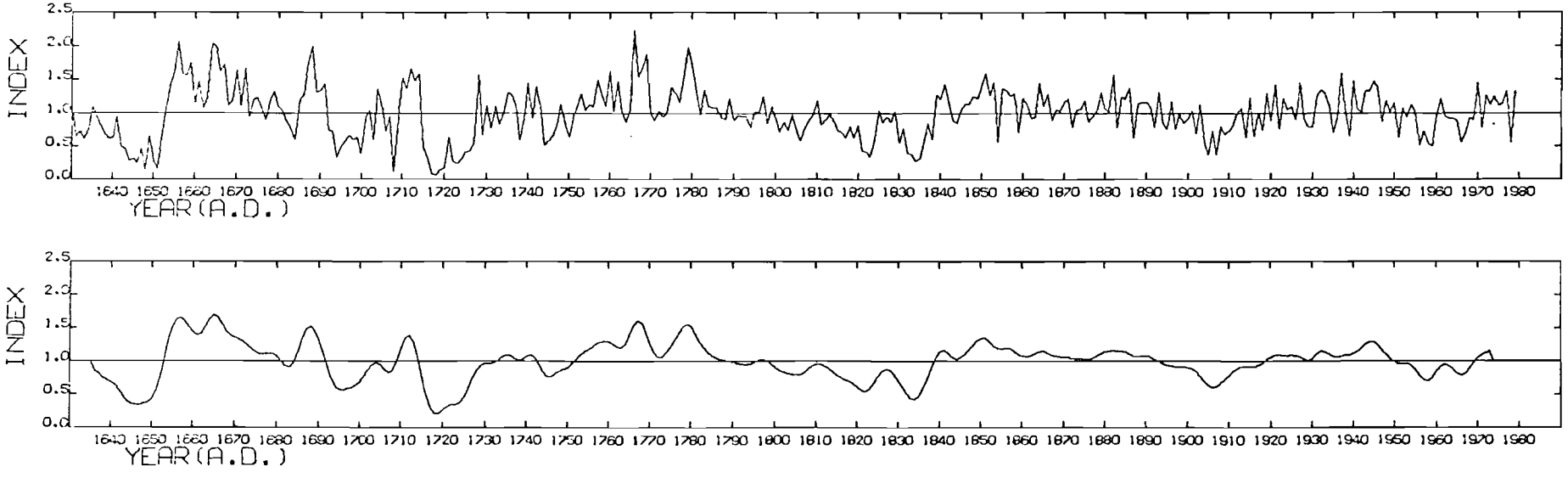
Interval analysed (A.D.) *1877-1961*
No. trees *6* No. radii *2*
Analysis of variance (% variance explained):

Mean chronology	*24.96*
Differences between trees	*30.46*
Other	*44.58*

Cross-correlation analysis:

Radii within trees	*0.56*
Radii among trees	*0.26*
Between tree means	*0.29*

UTV811 NOTHOFAGUS MENZIESII FIORDLAND 10 TREES, 16 RADII



UTV611 NOTHOFAGUS MENZIESII FIORDLAND

YEAR	0	1	2	3	4	5	6	7	8	9
1622			1.63	1.04	1.29	1.39	1.10	1.22	0.66	0.68
1630	1.14	0.63	0.73	0.59	0.74	1.08	0.96	0.81	0.68	0.61
1640	0.62	0.95	0.49	0.45	0.28	0.31	0.24	0.46	0.13	0.66
1650	0.29	0.14	0.63	1.05	1.39	1.59	2.07	1.58	1.55	1.75
1660	1.15	1.47	1.07	1.22	2.04	1.98	1.63	1.73	1.11	1.18
1670	1.64	1.10	1.68	0.94	1.20	1.22	1.06	0.89	1.18	1.32
1680	1.10	1.02	0.85	0.76	0.60	1.19	1.26	1.75	1.99	1.29
1690	1.33	1.44	0.73	0.72	0.32	0.48	0.57	0.66	0.59	0.62
1700	0.39	0.91	1.05	0.60	1.36	1.14	0.72	0.95	0.11	0.92
1710	1.52	1.36	1.67	1.47	1.58	0.47	0.32	0.07	0.06	0.14
1720	0.16	0.65	0.27	0.24	0.29	0.41	0.42	0.53	1.57	0.67
1730	1.11	0.77	1.11	0.83	0.99	1.29	1.27	1.09	0.58	0.90
1740	1.45	0.92	1.39	1.11	0.51	0.58	0.65	0.82	1.13	0.83
1750	0.64	0.92	1.10	1.29	1.04	1.12	1.09	1.50	1.28	1.10
1760	1.63	1.02	1.48	1.01	0.86	1.05	2.23	1.53	1.68	1.88
1770	0.99	0.88	1.02	0.95	0.99	1.38	1.31	1.16	1.51	1.98
1780	1.71	1.37	0.97	1.34	1.10	1.07	1.07	0.94	0.90	1.21
1790	0.89	0.96	0.94	0.95	0.78	1.02	1.00	1.25	0.84	1.09
1800	0.92	0.70	0.86	0.74	0.97	0.76	0.57	0.77	0.89	0.97
1810	1.18	0.82	0.89	0.98	0.88	0.73	0.70	0.62	0.80	0.63
1820	0.81	0.42	0.41	0.34	0.59	1.04	0.85	0.93	0.86	1.03
1830	0.53	0.77	0.38	0.37	0.27	0.31	0.58	0.85	0.60	1.27
1840	1.21	1.43	1.16	0.89	0.84	1.04	1.13	1.13	1.25	1.21
1850	1.40	1.60	1.26	1.45	0.56	1.37	1.34	1.26	1.28	0.71
1860	1.22	1.14	0.91	0.94	1.45	1.10	1.28	0.88	1.04	1.03
1870	1.16	1.21	0.78	1.05	1.06	1.19	0.86	0.94	1.04	1.31
1880	1.04	1.03	1.57	0.77	1.23	1.20	1.37	0.63	1.14	1.15
1890	1.15	1.10	0.78	1.30	0.84	0.75	1.17	0.75	0.99	0.85
1900	0.91	1.03	0.68	1.12	0.56	0.37	0.74	0.37	0.79	0.69
1910	0.73	0.81	1.01	1.08	0.62	1.22	0.65	1.01	0.73	1.29
1920	0.89	1.43	0.76	1.22	1.04	1.10	0.90	1.46	0.92	0.78
1930	0.78	1.25	1.34	1.30	1.11	0.70	0.93	1.59	0.99	0.64
1940	1.47	1.06	1.00	1.33	1.32	1.47	1.39	0.86	1.18	1.01
1950	1.14	0.62	1.07	0.93	1.12	1.02	0.51	0.74	0.53	0.48
1960	0.97	1.22	0.94	0.91	0.91	0.88	0.54	0.70	0.91	0.89
1970	1.45	0.77	1.27	1.12	1.25	1.10	1.15	1.33	0.54	1.32

The ring width index for each year was derived from 1 radius for the period 1622-1722; 2, 1723-1739; 3, 1740-1739; 3, 1740-1756; 4, 1757-1778; 5, 1779-1783; 6, 1784-1790; 7, 1791-1809; 8, 1810-1838; 9, 1839; 10, 1840-1845; 11, 1846-1854; 13, 1855-1859; 14, 1860-1865; 15, 1866-1876; 16, 1877-1909; 15, 1910-1961; 13, 1962-1979.

SITE AND COLLECTION INFORMATION

Site name *Windy Creek* Site code *WDC*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'S* Longitude *171°35'E*
Grid reference *NZMS1 S66 076104*
Species collected *Nothofagus solandri*
No. trees sampled *14* No. cores *27* No. discs *0*
Altitude *1350 m* Aspect *NW* Slope *30°*
Date of collection *17 December 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located on the northeast side of the Grey Range in the upper Harper River catchment (Craigieburn Forest Park). Access is from State Highway 73 at Cass, via Cass Saddle and Hamilton Hut, or at Bealey, via Lagoon Saddle. The site is a full days walk from from the road. Windy Creek is followed until a very prominent scree slope on the true right-hand side not far from the upper limit of forest, is reached. Trees were sampled on the upstream side of this scree near timberline. The monotypic Nothofagus solandri canopy is at about 6 to 10 m. Associated species include Podocarpus nivalis and Coprosma species. The substrate is rocky and drainage good.

CHRONOLOGY STATISTICS

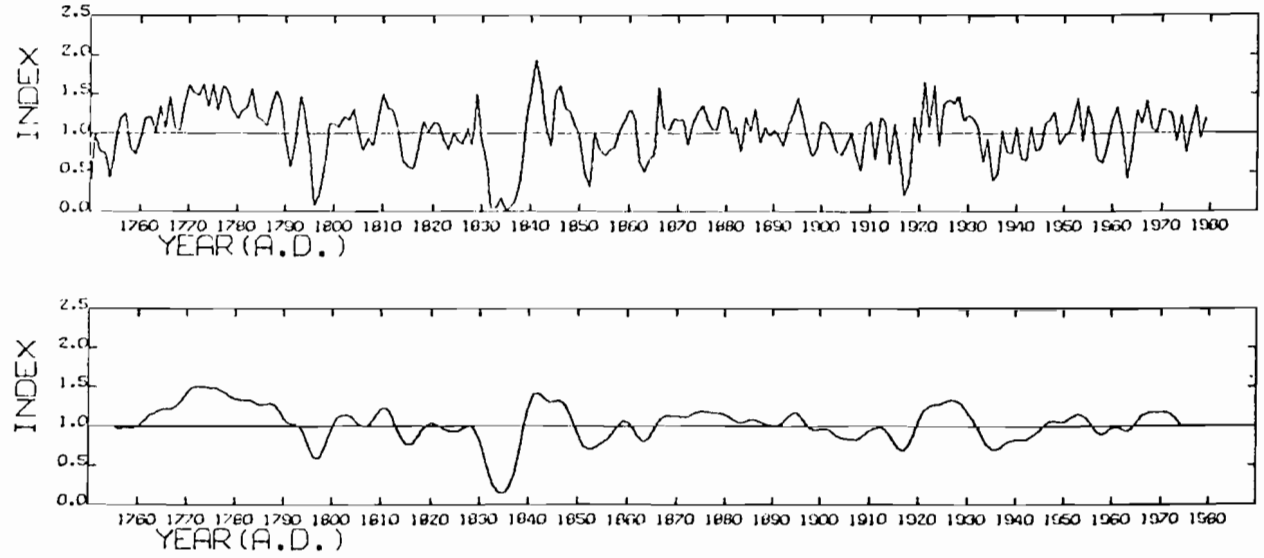
Chronology code	*WDC616*	Interval (A.D.)	*1747-1979*
No. trees	*11*	No. radii	*22*
Mean ring width (mm)	*1.13*	% absent rings	*1.01*
Autocorrelation	*0.59*		
Mean sensitivity	*0.30*		
Mean standard error	*0.10*		

SAMPLE STATISTICS

Interval analysed (A.D.) *1870-1979*
No. trees *8* No. radii
Analysis of variance (% variance explained):
- Mean chronology *39.13*
- Differences between trees *11.41*
- Other *49.46*

Cross-correlation analysis:
- Radii within trees *0.55*
- Radii among trees *0.41*
- Between tree means *0.42*

WDC616 NOTHOFAGUS SOLANDRI CANTERBURY 11 TREES, 22RADII



WDC616 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1747								0.55	0.87	0.47
1750	0.34	1.00	0.75	0.75	0.43	0.88	1.20	1.26	0.81	0.73
1760	0.94	1.20	1.21	1.01	1.35	1.06	1.48	1.06	1.02	1.37
1770	1.61	1.51	1.47	1.63	1.33	1.61	1.28	1.60	1.54	1.28
1780	1.18	1.29	1.33	1.57	1.21	1.16	1.10	1.35	1.53	1.41
1790	0.92	0.57	0.90	1.48	1.22	0.79	0.07	0.23	0.53	1.12
1800	1.12	1.07	1.21	1.16	1.31	1.00	0.76	0.94	0.83	1.21
1810	1.50	1.31	1.28	1.06	0.64	0.56	0.53	0.82	1.15	1.00
1820	1.14	1.12	0.92	0.78	0.98	0.90	0.85	1.06	0.84	1.50
1830	0.88	0.61	0.03	0.04	0.17	0.00	0.06	0.14	0.42	1.10
1840	1.53	1.94	1.61	1.07	0.83	1.50	1.61	1.31	1.25	1.07
1850	0.94	0.48	0.31	1.00	0.78	0.71	0.76	0.82	1.03	1.15
1860	1.30	1.22	0.64	0.49	0.66	0.72	1.59	1.06	1.02	1.18
1870	1.16	1.17	0.85	1.15	1.27	1.34	1.17	1.03	1.04	1.33
1880	1.29	0.99	1.09	0.75	1.21	1.02	1.30	0.87	1.07	0.96
1890	1.03	0.95	0.82	1.10	1.25	1.45	1.21	0.93	0.70	0.79
1900	1.15	1.11	0.98	0.75	0.71	0.84	1.00	0.71	0.51	1.09
1910	1.15	0.65	1.20	1.13	0.60	1.12	0.72	0.19	0.37	1.21
1920	0.87	1.64	1.07	1.61	0.83	1.37	1.42	1.37	1.47	1.14
1930	1.21	1.17	1.06	0.62	0.94	0.39	0.47	1.03	0.74	0.74
1940	1.07	0.65	0.64	1.09	0.77	0.79	1.12	1.17	1.27	0.85
1950	0.96	1.01	1.18	1.44	0.88	1.35	1.13	0.65	0.61	0.84
1960	1.15	1.34	1.01	0.41	0.81	1.28	1.11	1.41	1.04	1.00
1970	1.29	1.27	1.23	0.89	1.21	0.74	1.07	1.35	0.92	1.18

The ring width index for each year was derived from 1 radius for the period 1747-1761; 2, 1762-1779; 3, 1780-1791; 4, 1792-1802; 5, 1803; 6, 1804; 7, 1805-1838; 8, 1839; 11, 1840-1845; 12, 1846-1847; 13, 1848; 14, 1849-1853; 16, 1854-1869; 18, 1870-1879; 22, 1880-1979.

SITE AND COLLECTION INFORMATION

Site name *Waterfall Terrace* Site code *WFT*
Location *Cass Basin, Canterbury*
Latitude *43°01'S* Longitude *171°44'E*
Grid reference *NZMS1 S66 213185*
Species collected *Nothofagus solandri*
No. trees sampled *10* No. cores *11* No. discs *0*
Altitude *610 m* Aspect *SE* Slope *5°*
Date of collection *27 February 1980*
Collectors *D.A.Norton*

Site description:

This site is located on the prominent glacial surface under Mount Horrible to the northwest of the Cass River. Access is on foot from State Highway 73 at the Cass River bridge. Scattered groups of young Nothofagus solandri trees occur across an otherwise densely scrub covered terrain. This site is in one such group which consists of one large, fire scarred tree and several (up to 50) younger, even-aged trees. The large tree is presumably the seed source for the younger trees.

CHRONOLOGY STATISTICS

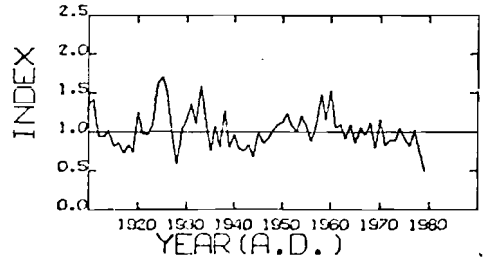
Chronology code	*WFT612*	Interval (A.D.)	*1904-1979*
No. trees	*7*	No. radii	*8*
Mean ring width (mm)	*3.45*	% absent rings	*0*
Autocorrelation	*0.42*		
Mean sensitivity	*0.24*		
Mean standard error	*0.08*		

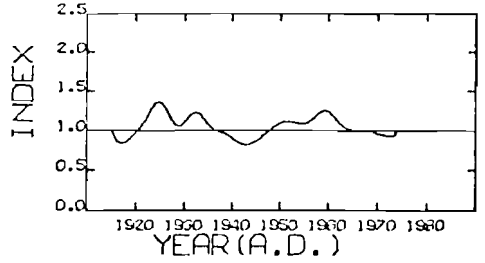
SAMPLE STATISTICS

Interval analysed (A.D.)
No. trees No. radii
Analysis of variance (% variance explained):
- Mean chronology
- Differences between trees
- Other

Cross-correlation analysis:
- Radii within trees
- Radii among trees
- Between tree means

WFT612 NOTHOFAGUS SOLANDRI CANTERBURY





WFT612 NOTHOFAGUS SOLANDRI CANTERBURY

YEAR	0	1	2	3	4	5	6	7	8	9
1904					0.93	0.64	0.44	0.61	0.27	1.23
1910	1.36	1.42	0.94	0.93	1.02	0.81	0.86	0.71	0.81	0.73
1920	1.26	0.97	0.95	1.10	1.63	1.70	1.51	0.93	0.59	1.04
1930	1.15	1.35	1.09	1.59	1.18	0.75	1.07	0.80	1.26	0.80
1940	0.98	0.77	0.76	0.83	0.67	1.00	0.84	0.91	1.02	1.10
1950	1.13	1.23	1.07	0.99	1.21	1.07	0.86	1.10	1.48	1.14
1960	1.54	1.04	1.10	0.91	1.10	0.86	1.06	0.94	1.12	0.78
1970	1.16	0.82	0.89	0.89	1.05	0.89	0.81	1.03	0.74	0.48

The ring width index for each year was derived from 1 radius for the period 1730-1739; 2, 1740-1752; 3, 1753-1759; 4, 1760-1763; 5, 1764; 6, 1765-1769; 7, 1770-1772; 8, 1773-1789; 9, 1790-1799; 12, 1800-1830; 13, 1831-1832; 14, 1833-1839; 18, 1840-1868; 19, 1869-1879; 20, 1880-1979.

SITE AND COLLECTION INFORMATION

Site name	*Random*	Site code	*RANDOM*
Location			
Latitude		Longitude	
Grid reference			
Species collected			
No. trees sampled		No. cores	No. discs
Altitude		Aspect	Slope
Date of collection			
Collectors			

Site description:

This chronology was developed using random number series representing individual radii.

CHRONOLOGY STATISTICS

Chronology code	*RANDOM 600*	Interval (A.D.)	*1780-1979*
No. trees	*6*	No. radii	*12*
Mean ring width (mm)	*1.10*	% absent rings	*0.46*
Autocorrelation	*0.05*		
Mean sensitivity	*0.25*		
Mean standard error	*0.20*		

SAMPLE STATISTICS

Interval analysed (A.D.) *1880-1979*

No. trees *6* No. radii *2*

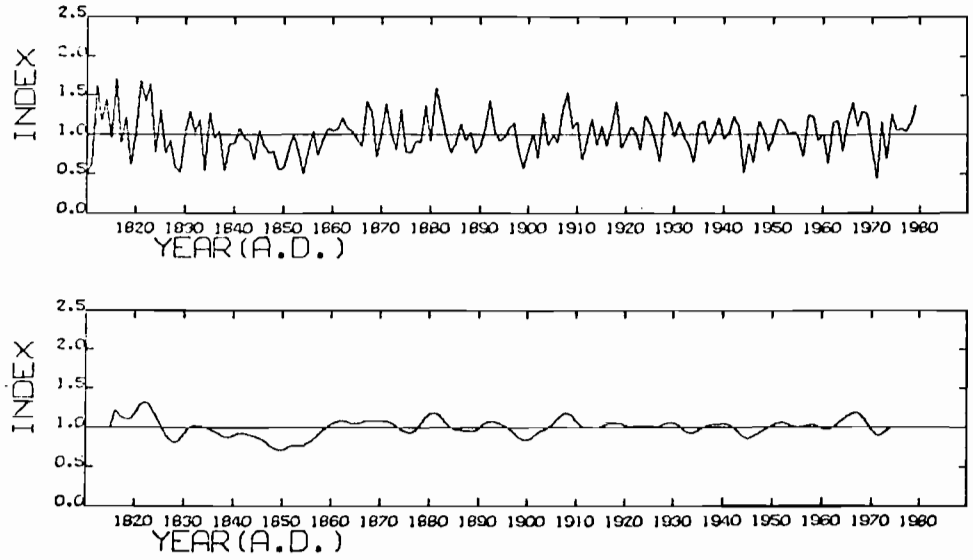
Analysis of variance (% variance explained):

Mean chronology	*2.96*
Differences between trees	*0.00*
Other	*97.04*

Cross-correlation analysis:

Radii within trees	-
Radii among trees	-
Between tree means	*0.09*

RANDOM DATA 6 TREES, 12 RADII



RANDOM DATA

YEAR	0	1	2	3	4	5	6	7	8	9
1810	0.50	0.61	1.63	1.17	1.46	0.95	1.70	0.89	1.23	0.60
1820	1.02	1.68	1.42	1.64	0.77	1.30	0.76	0.92	0.57	0.50
1830	1.04	1.29	1.02	1.18	0.54	1.28	0.95	1.04	0.53	0.89
1840	0.88	1.08	0.95	0.91	0.66	1.05	0.86	0.76	0.78	0.54
1850	0.56	0.80	1.01	0.79	0.49	0.78	1.04	0.73	0.92	1.08
1860	1.04	1.06	1.21	1.07	1.03	0.93	0.84	1.42	1.27	0.71
1870	1.04	1.40	1.00	0.80	1.32	0.77	0.76	0.91	0.89	1.37
1880	0.91	1.60	1.27	0.95	0.76	0.90	1.13	0.91	1.04	0.76
1890	0.84	1.07	1.43	1.05	0.91	0.96	1.08	1.14	0.78	0.56
1900	0.82	1.03	0.69	1.28	0.86	0.98	0.89	1.30	1.54	1.07
1910	1.16	0.67	0.93	1.20	0.85	1.11	0.85	1.10	1.42	0.82
1920	0.95	1.10	1.02	0.79	1.24	1.14	0.93	0.65	1.28	1.22
1930	0.95	1.16	0.95	0.85	0.63	1.12	1.17	0.87	1.00	1.21
1940	0.93	0.99	1.22	1.09	0.51	0.89	0.63	1.16	1.05	0.78
1950	0.97	1.20	1.15	1.00	1.04	0.96	0.71	1.25	1.23	0.93
1960	0.99	0.62	1.15	1.18	0.78	1.19	1.41	1.10	1.30	1.24
1970	0.79	0.44	1.16	0.69	1.26	1.04	1.07	1.04	1.15	1.37

The "ring width" index for each year was derived from 2 radii for the period 1780-1789; 3, 1790-1809; 6, 1810-1819; 8, 1820-1829; 10, 1830-1839; 11, 1840-1879; 12, 1880-1979.

Site name *Armstrong Reserve* Site code *ARM*
Location
Latitude Longitude
Grid reference
Species collected
No. trees sampled No. cores No. discs
Altitude Aspect Slope
Date of collection
Collectors

Site description:

See LaMarche et al. (1979c page 44) for full details.

CHRONOLOGY STATISTICS

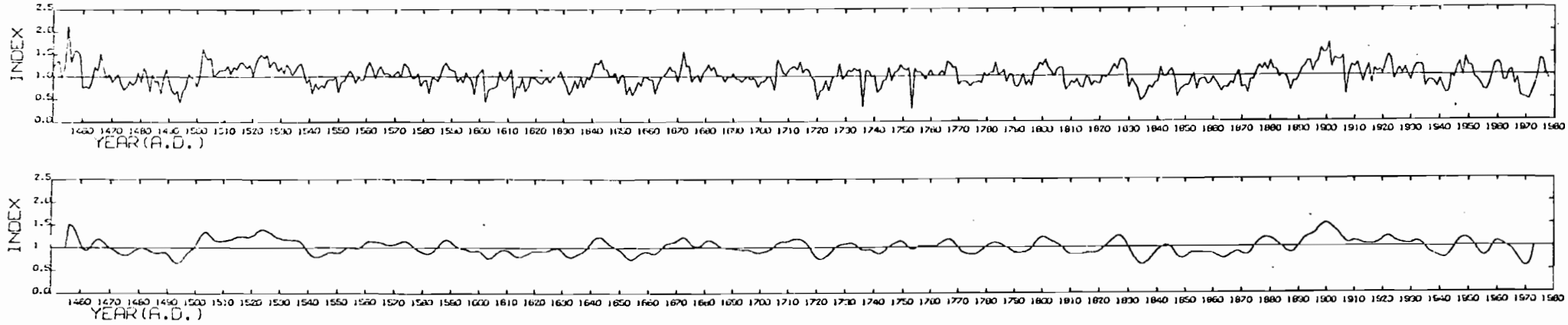
Chronology code *ARM189* Interval (A.D.)
No. trees No. radii
Mean ring width (mm) % absent rings
Autocorrelation
Mean sensitivity
Mean standard error

SAMPLE STATISTICS

Interval analysed (A.D.)
No. trees No. radii
Analysis of variance (% variance explained):
- Mean chronology
- Differences between trees
- Other

Cross-correlation analysis:
- Radii within trees
- Radii among trees
- Between tree means

ARM189 LIBOCEDRUS BIDWILLII BANKS PENNINSULA 13 TREES, 41 RADII



ARM189 LIBOCEDRUS BIDWILLII BANKS PENNINSULA

YEAR	0	1	2	3	4	5	6	7	8	9
1450	1.22	1.31	1.37	0.96	1.23	2.15	1.31	1.57	1.58	1.48
1460	0.75	0.79	0.74	0.90	1.23	1.12	1.53	1.19	0.97	1.05
1470	0.88	0.96	1.06	0.83	0.70	0.76	0.91	0.81	0.88	1.10
1480	0.88	1.21	1.04	0.66	1.06	0.88	0.91	0.63	0.96	1.17
1490	0.91	0.69	0.61	0.69	0.41	0.69	0.78	1.06	0.99	0.93
1500	0.78	1.02	1.63	1.45	1.38	1.43	0.98	1.07	1.14	1.15
1510	1.15	1.25	1.06	1.23	1.16	1.29	1.34	1.26	1.19	1.28
1520	1.03	1.28	1.42	1.50	1.41	1.50	1.20	1.34	1.31	1.12
1530	1.22	1.08	1.28	1.19	1.03	1.14	1.25	1.30	1.07	0.85
1540	0.97	0.63	0.85	0.71	0.81	0.75	0.92	0.94	0.92	0.99
1550	0.64	0.88	0.90	1.03	1.12	1.03	0.85	1.00	0.91	0.94
1560	1.21	1.32	1.16	0.95	1.16	1.23	1.05	1.07	1.05	0.97
1570	1.07	1.12	0.98	1.30	1.24	1.11	0.95	0.97	1.07	0.79
1580	0.91	0.93	0.63	0.98	0.95	0.89	1.06	1.25	1.31	1.18
1590	1.14	1.12	0.89	0.98	0.86	1.10	0.99	0.92	0.60	1.03
1600	1.10	1.18	0.43	0.70	0.74	0.75	0.79	1.12	0.92	0.91
1610	1.01	1.17	0.53	0.80	0.75	0.97	0.67	0.75	0.99	0.97
1620	0.94	0.88	0.84	0.94	0.98	0.86	0.97	0.97	1.02	1.12
1630	0.93	0.80	0.60	0.73	0.93	0.74	1.00	0.76	0.98	0.93
1640	1.10	1.31	1.27	1.39	1.16	1.16	1.01	1.02	1.09	0.85
1650	1.04	1.05	0.60	0.79	0.59	0.70	0.89	0.79	1.00	0.97
1660	0.93	0.94	0.63	0.85	0.98	1.02	1.09	1.23	1.12	1.14
1670	0.87	1.18	1.56	1.22	1.25	0.87	0.99	1.04	0.88	1.09
1680	1.15	1.28	1.13	1.23	1.03	1.04	1.00	0.88	1.00	0.98
1690	1.07	0.94	0.94	0.87	0.94	1.02	0.93	0.96	0.91	0.75
1700	0.87	0.87	0.96	1.02	0.88	0.69	1.37	1.25	1.07	1.03
1710	1.14	1.19	1.23	1.14	1.33	1.08	1.17	1.14	0.97	0.91
1720	0.49	0.69	0.70	0.91	0.68	0.93	1.03	0.97	1.29	0.92
1730	1.02	1.14	1.09	1.17	1.11	1.16	0.33	1.13	1.12	0.97
1740	1.03	0.64	0.70	0.90	0.93	1.19	0.89	1.09	1.11	1.25
1750	1.17	1.13	1.19	0.28	1.17	1.08	1.09	1.02	0.93	1.05
1760	1.12	1.01	0.99	1.03	1.11	1.03	1.32	1.28	1.17	1.20
1770	0.80	0.88	0.89	0.85	0.76	0.84	0.84	0.87	0.83	1.06
1780	0.98	1.07	1.06	1.30	1.03	1.05	1.12	0.85	1.04	1.04
1790	0.78	0.75	0.88	1.05	0.79	0.91	0.77	1.11	1.13	1.30
1800	1.23	1.36	1.17	1.10	0.97	1.14	1.19	1.17	0.69	0.76
1810	0.87	0.82	0.92	0.76	0.73	0.97	0.96	0.78	0.89	0.84
1820	0.82	1.01	0.96	1.03	1.13	1.26	1.14	1.36	1.37	1.28
1830	0.73	0.93	0.81	0.71	0.45	0.50	0.62	0.78	0.71	0.85
1840	0.86	1.19	0.98	0.99	1.09	1.16	0.96	0.52	0.69	0.74
1850	0.77	0.78	0.93	1.05	0.69	0.90	0.92	0.94	0.80	0.83
1860	0.96	0.86	0.77	0.64	0.75	0.72	0.85	0.80	1.00	1.10
1870	0.73	0.78	0.61	0.92	0.90	1.09	1.23	1.14	1.26	1.10
1880	1.32	1.12	1.14	0.94	1.02	1.00	0.90	0.66	0.88	0.86
1890	1.00	1.14	1.20	1.32	1.32	1.07	1.26	1.32	1.60	1.50
1900	1.53	1.72	1.18	1.40	1.35	1.34	1.43	0.57	1.02	1.23
1910	1.17	1.28	1.05	0.84	1.08	1.24	0.82	1.15	1.07	1.12
1920	1.02	1.26	1.45	1.35	0.90	1.05	1.16	1.03	1.18	0.99
1930	0.86	1.12	1.22	1.22	1.23	0.73	0.87	0.88	0.84	0.72
1940	0.91	0.73	0.59	0.63	0.99	0.91	1.18	1.29	0.96	1.40
1950	1.19	1.20	0.93	0.89	0.80	0.68	0.64	0.75	0.99	1.23
1960	1.28	1.20	0.85	0.86	1.08	1.10	0.76	0.92	0.53	0.50
1970	0.47	0.44	0.61	0.79	0.98	1.35	1.34	1.01	0.90	

SITE AND COLLECTION INFORMATION

Site name *Camoflauge Creek* Site code *CMF*
Location *Murchison Mountains, Fiordland*
Latitude *45°09'S* Longitude *167°32'E*
Grid reference *NZMS1 S140 594498*
Species collected *Nothofagus solandri*
No. trees sampled *12* No. cores *19* No. discs *0*
Altitude *1050 m* Aspect *N* Slope *30°*
Date of collection *31 January 1981*
Collectors *D.A.Norton*

Site description:

This site is located near the head of the South West Arm of the Middle Fiord, Lake Te Anau, in Fiordland National Park. The site is located within the Takahe Special Area and a permit is needed to visit the area. Access was by helicopter but boat access is also possible. The site is on the prominent spur to the west of Camoflauge Hut (unofficial name). Trees were sampled immediately below timberline. The canopy at about 8 m is formed by large, often gnarled Nothofagus menziesii trees. No other canopy trees are present. A dense shrub layer includes Archeria traversii, Coprosma species, Dracophyllum species, Hebe species, Myrsine divaricata, Pseudopanax colensoi and Senecio benettii. An abundance of herbs grow on the forest floor.

SITE AND COLLECTION INFORMATION

Site name *Cox Saddle* Site code *COX*
Location *Poulter Valley, Canterbury*
Latitude *42°46'S* Longitude *171°54'E*
Grid reference *NZMS1 S59 364478*
Species collected *Nothofagus solandri*
No. trees sampled *4* No. cores *8* No. discs *0*
Altitude *1100 m* Aspect *SW* Slope *20°*
Date of collection *14 January 1982*
Collectors *D.A.Norton and R.K.Harper*

Site description:

Cox Saddle connects the main and east branches of the Poulter River in Arthurs Pass National Park. Access is from Cass via Mount White Bridge to the Andrews River by car. One days walk up the Andrews, Casey and Poulter Rivers reaches the junction of the Poulter River and Thompson Stream. A further half days walk up Thompson Stream and Cherrywood Creek leads to Cox Saddle. Trees were sampled in monotypic Nothofagus solandri forest to the south of Cox Saddle. The canopy is at about 8-10m and a dense shrub layer, including Olearia colensoi, O.lacunosa, Podocarpus nivalis, Coprosma species, Phyllocladus alpinus and Dracophyllum longifolium is present.

SITE AND COLLECTION INFORMATION

Site name *Fettes Glacier* Site code *FET*
Location *Landsborough Valley*
Latitude *43°47'S* Longitude *169°53'E*
Grid reference *NZMS1 S88 578258*
Species collected *Nothofagus menziesii*
No. trees sampled *5* No. cores *8* No. discs *0*
Altitude *800 m* Aspect *SE* Slope *5-15°*
Date of collection *18 February 1983*
Collectors *D.A.Norton and R.K.Harper*

Site description:

Access to this site is difficult, being four days walk from the Haast Pass road. Access here was by helicopter. The site sampled is located on the true right-hand side of the Landsborough River and about 500 m downstream from Whitcombe Creek (draining the Fettes and Townsend Glaciers). The Nothofagus menziesii forest appears to be invading a subalpine scrub community and scattered trees to about 12 m tall were sampled amongst a diverse scrub community including Dracophyllum longifolium, Olearia nummularifolia, O.ilicifolia, Myrsine divaricata, Hoheria glabrata, Coprosma rugosa and Carmichaelia grandiflora.

SITE AND COLLECTION INFORMATION

Site name *Harris Saddle* Site code *HRS*
Location *Hollyford Valley, Fiordland*
Latitude *44°45'S* Longitude *168°15'E*
Grid reference *NZMS1 S122 111047*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *27* No. discs *0*
Altitude *1040 m* Aspect *W* Slope *10-20°*
Date of collection *25 November 1981*
Collectors *D.A.Norton and R.K.Harper*

Site description:

The Routeburn Track traverses above timberline in the Hollyford Valley for several kilometres. Approximately 1 km south of Harris Saddle the Deadmans Track descends from this to the floor of the Hollyford Valley. Nothofagus menziesii trees were sampled in close proximity to this latter track immediately below the timberline margin. Canopy trees were sampled. The pure N.menziesii forest consists of trees of both straight boled and gnarled growth form up to 16 m tall, with associated species, including Coprosma pseudocuneata, Pseudopanax colensoi and Phyllocladus alpinus, forming a dense shrub layer.

SITE AND COLLECTION INFORMATION

Site name *Hut Bush* Site code *HTB*
Location *Cropp River, Westland*
Latitude *43°05'S* Longitude *170°58'E*
Grid reference *NZMS1 S64 523115*
Species collected *Libocedrus bidwillii*
No. trees sampled *176* No. cores - No. discs *3*
Altitude *930 m* Aspect *N* Slope *30-50°*
Date of collection *January 1980*
Collectors *D.A.Norton and A.E.Moore*

Site description:

This site is located in the Cropp River catchment, a tributary of the Whitcombe and Hokitika Rivers. Access was by helicopter; foot access from the Hokitika River road end (35 km south of Hokitika township) takes two days. The site is on the hill slope immediately behind the NZ Forest Service Cropp River hut, located on the true right-hand side of the river. The site is on a steep face and trees were sampled predominantly on the upper part and on spurs descending towards the valley floor.

Archeria traversii, Coprosma pseudocuneata, Dracophyllum traversii and D.longifolium form the forest canopy at about 3 to 5 m. Libocedrus bidwillii and more rarely Podocarpus hallii and and Dacrydium biforme occur as emergents and are often of a flag form. Various shrub species, tree seedlings, herbs, ferns and bryophytes form the ground layer.

SITE AND COLLECTION INFORMATION

Site name *Key Summit* Site code *KEY*
Location *Hollyford Valley, Fiordland*
Latitude *44°50'S* Longitude *168°15'E*
Grid reference *NZMS1 S122 085938*
Species collected *Nothofagus menziesii*
No. trees sampled *15* No. cores *27* No. discs *0*
Altitude *1000 m* Aspect *E* Slope *10-20°*
Date of collection *21 November 1981*
Collectors *D.A.Norton and R.K.Harper*

Site description:

This site is located one to two hours walk from the Te Anau-Milford highway along a well formed track. The track is followed to the top of Key Summit. Nothofagus menziesii trees were sampled on the slopes above Lake Howden. Large trees form the canopy at about 10-12 m. The dense subcanopy scrub layer consists of thickets of Coprosma ciliata, C.pseudocuneata, Olearia ilicifolia and Archeria traversii. Soils are moderately gleyed and drainage poor.

SITE AND COLLECTION INFORMATION

Site name *Manuka Point* Site code *MKP*
Location *Rakaia Valley, Canterbury*
Latitude *43°15'S* Longitude *171°12'E*
Grid reference *NZMS1 S73 742841*
Species collected *Nothofagus solandri*
No. trees sampled *4* No. cores *8* No. discs *0*
Altitude *1050 m* Aspect *S* Slope *15-35°*
Date of collection *29 October 1981*
Collectors *D.A.Norton*

Site description:

This site is located on the ridge separating the Rakaia and Mathias Rivers. Trees were cored close to the upper limit of forest. Access is up the formed road on the south bank of the Rakaia River to near Glenfalloch homestead. Access was by helicopter but foot access is not difficult and would take about two hours via Manuka Point homestead. The site consists of young even-aged trees on the south side of the ridge. Buried forest soils are common under a depleted and eroding Celmisia spectabilis-Festuca novae-zelandia grassland beyond the present forest. Stumps of large old trees are present within the forest. It seems fairly obvious that the site has been burnt and the present trees established subsequently. Various shrub and herbaceous species are present within the forest.

SITE AND COLLECTION INFORMATION

Site name *Te Ana-au Caves* Site code *TAC*
Location *Murchison Mountains, Fiordland*
Latitude *45°15'S* Longitude *167°40'E*
Grid reference *NZMS1 S140 747348*
Species collected *Nothofagus solandri, N.menziesii*
No. trees sampled *10* No. cores *16* No. discs *0*
Altitude *600 m* Aspect *E* Slope *0-10°*
Date of collection *3 February 1981*
Collectors *D.A.Norton and C.J.Burrows*

Site description:

This site is located on the lower part of the track descending from Takahe Valley to Lake Te Anau. No conspicuous features are present along the track to pin-point the site's location, but trees were sampled close to the track on a small terrace just above the main area of Nothofagus fusca forest. The mixed Nothofagus solandri-N.menziesii forest is tall (to 20 m) and a diverse shrub and ground flora is present. Blechnum discolour forms a thick carpet over the forest floor and shrub and small tree species include Carpodetus serratus, Griselinia littoralis, Weinmannia racemosa and Pseudopanax simplex.

SITE AND COLLECTION INFORMATION

Site name *Trilogy avalanche tracks* Site code *TAT*
Location *Craigieburn Range, Canterbury*
Latitude *43°05'S* Longitude *171°43'E*
Grid reference *NZMS1 S66 176093*
Species collected *Nothofagus solandri*
No. trees sampled *3* No. cores *0* No. discs *3*
Altitude *1070 m* Aspect - Slope -
Date of collection *16 February 1981*
Collectors *D.A.Norton and A.E.Moore*

Site description:

Several avalanche tracks descend to the valley floor in the upper Cass Valley. The three logs sampled were buried under approximately 30 to 60 cm of alluvial material in the fan at the base of the Cass 6 avalanche track. The site is close to the track, approximately one and a half hours up the Cass Valley from the University of Canterbury Cass Field Station. Discs were taken from the three buried logs.

APPENDIX FIVE

SHOOT EXTENSION DATA

The cumulative percentage of seasonal *Nothofagus solandri* shoot growth, ± one standard deviation, for two growing seasons is listed below. This data is used in Fig. 2.5. n=number of shoots measured. Measurements during winter are not included as cumulative growth equalled 100%.

A5.1 Sugarloaf Bush

	TREE 1 (n=8)	2 (n=14)	3 (n=26)	4 (n=7)	5 (n=37)
20. 9.80	0	0	0	0	0
12.10.80	8±11	3±3	9±12	9±3	8±6
29.10.80	32±13	14±7	18±16	34±16	12±8
9.11.80	51±19	23±8	35±17	51±25	17±12
25.11.80	85±7	59±14	61±17	76±12	44±17
5.12.80	85±19	84±11	78±13	88±5	65±18
24.12.80	93±8	92±7	92±8	95±4	93±7
8. 1.81	96±8	92±7	94±6	94±4	95±5
20. 1.81	100±4	97±4	96±5	95±3	97±4
5. 2.81	99±6	100±3	98±6	100±3	98±4
24. 2.81	100	100±1	98±4	99±2	98±5
1. 4.81	100	100	100	100	100
17. 9.81	0	0	0	0	0
18.10.81	8±7	3±4	2±2	3±4	2±4
2.11.81	24±20	12±12	13±10	16±9	11±18
16.12.81	90±12	98±4	91±12	89±14	93±9
27.12.81	85±22	99±3	95±6	97±4	92±13
12. 1.82	92±19	99±2	99±3	92±16	98±4
1. 2.82	101±2	101±2	99±2	98±4	99±2
24. 2.82	100	100	100	100	100

A5.2 Subalpine Forest

	TREE 1 (n=28)	2 (n=25)
30.10.80	0	0
13.11.80	0	2±5
26.11.80	5±8	7±9
10.12.80	7±7	10±10
23.12.80	18±11	30±11
7. 1.81	59±17	74±15
19. 1.81	93±8	94±5
9. 2.81	100±2	98±4
26. 2.81	100	100
	(n=22)	(n=19)
16.10.81	0	0
3.11.81	3±6	4±6
7.12.81	12±10	17±13
28.12.81	72±16	61±20
24. 1.82	93±9	87±11
4. 2.82	100±2	98±3
25. 2.82	100	100

A5.3 Timberline Margin

TREE	1 (n=19)	2 (n=18)	3 (n=19)	4 (n=10)	5 (n=19)	6 (n=10)
13.11.80	0	0	0	0	0	0
26.11.80	7±6	7±9	9±9	10±8	9±8	12±9
10.12.80	9±8	14±11	13±8	12±9	14±11	24±8
23.12.80	25±11	49±16	26±16	31±14	31±12	58±12
7. 1.81	64±15	75±15	68±14	74±13	73±12	82±10
19. 1.81	85±14	90±10	89±10	94±6	87±8	93±6
9. 2.81	97±5	98±4	97±8	99±4	96±6	97±6
26. 2.81	100	100	100	100	100	100
	(n=16)	(n=16)	(n=14)	(n=10)	(n=17)	(n=6)
16.10.81	0	0	0	0	0	0
3.11.81	2±4	5±7	3±3	2±4	0	0
7.12.81	11±7	20±10	17±10	14±10	14±14	37±14
28.12.81	69±18	75±17	67±19	71±20	78±21	88±8
24. 1.82	93±5	91±12	89±8	89±10	90±15	100±1
4. 2.82	99±3	100	99±2	100±1	100±1	100
25. 2.82	100	100	100	100	100	100

APPENDIX SIX

EXAMPLES OF SITE AND TREE INFORMATION RECORDED

Examples of a field site information sheet and of the information recorded for individual trees are given below.

A6.1 Site Information sheet

1. SITE CODE: *KEY*

2. SITE GRID REFERENCE: *NZMS1 S122 085938*
   Were site photos taken? (1) Yes 2) No

3. ALTITUDE OF SITE: *950-1050 m*

4. SLOPE ANGLE FROM HORIZONTAL: 1) 0^{o} 2) $1-10^{0}$ (3) $11-20^{0}$
   4) $21-30^{0}$ 5) $31-45^{0}$ 6) Greater than 45^{0}

5. DIRECTION SLOPE FACES: 1) N 2) NE (3) E 4) SE 5) S
   6) SW 7) W 8) NW 9) Flat 10) Variable

6. DIRECTION OF REGIONAL SLOPE: 1) N 2) NE (3) E 4) SE
   5) S 6) SW 7) W 8) NW 9) Flat

7. PHYSIOGRAPHY: 1) Flat 2) Concave (3) Convex 4) Spur
   5) Bluff

8. PREDOMINANT SOIL CHARACTERISTICS: 1) Organic (2) Clay (3) Silt
   4) Sand 5) Loam 6) Gravel 7) Rock fragments
   8) Bedrock 9) Other_____

9. PROFILE DEVELOPMENT: 1) None 2) Weak (3) Moderate 4) Strong

10. SOIL TYPE: *Podzolised high country yellow-brown earth*

11. SOIL DRAINAGE: 1) Good (2) Moderate 3) Poor 4) Variable

12. SOIL DEPTH: 1) <10 cm (2) 10-30 cm 3) >30 cm

13. SOIL CHEMISTRY; 1) Extreme saline 2) Extreme alkaline
    3) Extreme acid 4) Anaerobic 5) Other (6) No extremes

14. SOIL PARENT MATERIAL: 1) Igneous 2) Sandstone 3) Mudstone
    4) Limestone (5) Metamorphic 6) Loess 7) Alluvium
    8) Other_____ 9) Not observed

15. SPECIES COLLECTED; *Nothofagus menziesii*

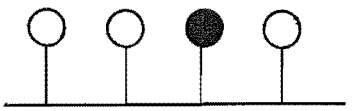
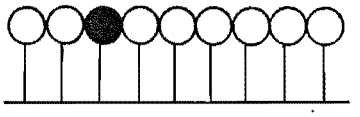
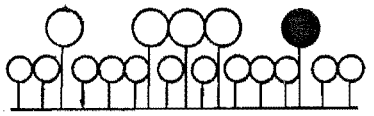
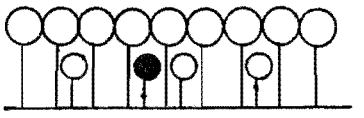
16. WAS COLLECTED SPECIES DOMINANT IN CROWN COVER? (1) Yes 2) No

17. WHAT % OF TOTAL FOREST WAS COLLECTED SPECIES? 1) 1-25%
2) 26-50% 3) 51-75% (4) 76-100%

18. ASSOCIATED SPECIES: Canopy -
Subcanopy *Coprosma ciliata, Archeria traversii, Oleria ilicifolia*
Ground *Polystichum vestitum, Hypolepis sp., Hymenophyllum spp.*

19. VEGETATION ZONE: *Subalpine silver beech forest*

20. WHAT BEST DESCRIBES THE POSITION OF THE SAMPLED TREES/SPECIES IN THE FOREST?

1) 
(2) 
3) 
4) 

21. FOREST GROWTH: 1) Natural, successional (2) Natural, stable
3) Cultivated a) native b) adventive

22. SITE DISTURBANCE: (1) No 2) Yes, anthropogenic
3) Yes, natural 4) Both 2 and 3 5) Unknown

23. IF DISTURBED WHAT TYPE OF DISTURBANCE? 1) Fire 2) Wind
3) Snow avalanche 4) Flood 5) Rock-fall 6) Debris flow
7) Insect epidemic 8) Snow-break 9) Ice-blast 10) Clear felling
11) Landslide/slip 12) Other _____

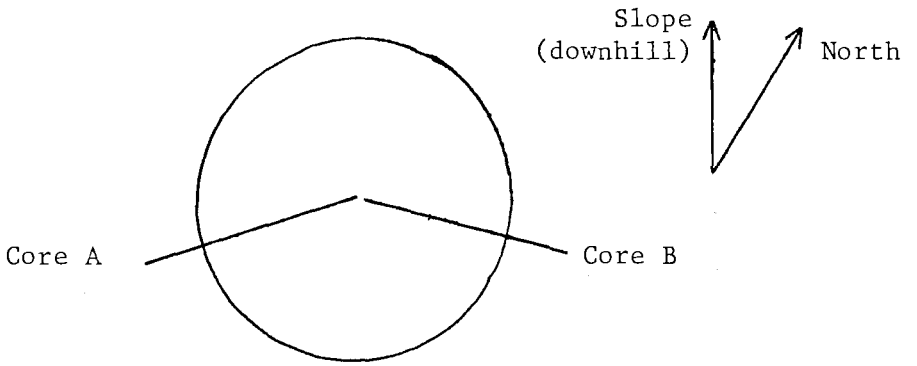
24. ARE CLIMATIC DATA AVAILABLE FROM LOCALE OF COLLECTION SITE?
1) Yes (2) No If yes give details *Milford Sound nearest climate station*

A6.2 Tree Information Sheet

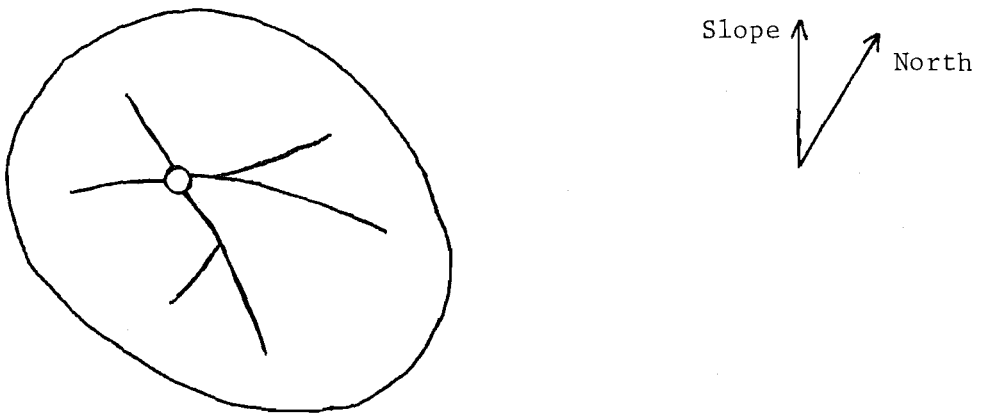
1. TREE CODE: *KEY5*
2. HEIGHT OF CORES AND DIAMETER: *1 m above ground DlM = 0.76*
3. HEIGHT OF TREE: *11 m*
4. HEIGHT TO FIRST BRANCHES: *4.5 m*
5. SINGLE OR MULTI-STEMMED: *single*
6. SLOPE: *15°*
7. ASPECT: *E*
8. SOIL DEPTH: *30 cm +*
9. SOIL DRAINAGE: *good*
10. CANOPY POSITION: *in canopy*
11. PRESENCE OF DEAD SPARS: *no*
12. SIGNS OF DAMAGE TO TREE: *no*

As well as noting the above, the following two diagrams were used:

1. To indicate position of cores



2. To indicate branching direction and canopy spread



APPENDIX SEVEN

CLIMATE AND RIVERFLOW RECONSTRUCTIONS

In this appendix the annual reconstructed values for New Zealand summer temperature, Amberley summer rainfall, Lake Coleridge summer rainfall and Hurunui summer riverflow are listed.

RECONSTRUCTION DATA
RECONSTRUCTION OF NEW ZEALAND SUMMER TEMPERATURE
CALIBRATION PERIOD: 1853 TO 1913, R=0.77
VERIFICATION PERIOD: 1914 TO 1974, R=0.70 RE=0.22
(ALL VALUES ARE IN DEGREES CELSIUS)

YEAR	0	1	2	3	4	5	6	7	8	9
1730	17.5	16.4	16.7	15.4	16.3	16.1	15.1	16.1	15.6	15.5
1740	16.3	15.4	15.9	16.2	14.6	15.7	14.8	15.4	15.6	15.2
1750	14.9	15.5	16.0	16.0	16.4	16.5	16.2	15.8	15.3	14.8
1760	14.9	14.7	15.9	14.8	15.2	14.5	16.4	15.6	15.1	15.5
1770	16.0	14.7	15.6	16.6	15.2	16.3	15.5	16.4	16.1	16.3
1780	16.8	16.1	15.5	16.2	15.2	15.4	15.2	15.9	15.0	16.3
1790	15.2	14.9	15.6	16.6	16.2	15.9	15.9	16.2	16.1	15.9
1800	16.3	15.5	15.8	15.8	15.9	16.9	14.6	15.2	15.8	15.4
1810	17.1	15.8	15.6	15.9	16.2	15.3	15.6	14.7	15.9	15.3
1820	15.7	14.8	15.9	15.2	15.2	15.8	15.3	16.4	14.7	16.4
1830	15.5	16.5	15.3	15.2	16.1	15.5	14.7	16.0	14.1	15.2
1840	15.6	16.1	15.5	15.8	14.9	13.7	15.5	15.0	14.8	15.5
1850	15.7	16.0	14.7	16.0	15.8	15.3	15.8	14.6	15.4	14.6
1860	15.4	16.3	15.4	15.1	16.3	15.5	16.5	15.2	15.3	15.7
1870	15.8	16.3	15.9	15.4	16.1	16.8	16.2	14.8	15.3	16.1
1880	16.0	15.2	17.3	15.0	16.2	15.5	16.8	15.1	16.1	16.3
1890	15.6	16.4	15.1	16.4	16.0	15.2	16.0	15.3	15.7	15.8
1900	15.3	15.4	15.3	15.9	15.4	14.8	16.6	16.2	14.5	15.9
1910	15.9	14.3	15.5	15.6	14.6	16.5	15.0	14.6	14.8	16.0
1920	15.2	16.3	14.3	16.4	14.6	15.4	15.1	16.1	15.2	14.7
1930	14.5	14.7	15.6	14.9	16.3	15.5	14.5	17.5	15.5	14.9
1940	16.0	15.4	15.1	15.8	15.3	15.6	15.3	15.4	15.1	14.9
1950	15.7	15.2	14.9	16.1	15.2	16.0	15.7	15.2	15.5	14.8
1960	15.1	16.4	16.2	15.0	15.8	16.4	15.3	16.7	16.3	16.5
1970	16.0	15.8	16.5	16.0	16.7					

RECONSTRUCTION OF AMBERLEY SUMMER RAINFALL
CALIBRATION PERIOD: 1925 TO 1974, R=0.68
VERIFICATION PERIOD: 1909 TO 1924, R=0.81 RE=0.48
(ALL VALUES ARE TOTAL RAINFALL IN MILLIMETRES)

YEAR	0	1	2	3	4	5	6	7	8	9
1840	51	195	147	168	231	114	24	192	105	126
1850	162	153	129	33	117	126	171	177	153	153
1860	204	216	189	195	132	186	147	204	165	147
1870	150	177	177	123	103	93	213	204	168	135
1880	159	174	108	183	111	84	177	189	126	126
1890	231	225	237	186	210	153	141	267	237	207
1900	234	267	231	126	225	138	108	141	219	183
1910	195	225	129	204	207	132	219	264	195	156
1920	192	138	231	114	207	153	111	171	216	228
1930	135	114	174	162	111	162	216	183	159	165
1940	114	225	165	60	291	210	195	162	168	156
1950	231	183	195	213	219	132	192	285	117	198
1960	165	156	177	261	117	138	201	270	177	138
1970	144	135	147	150	129					

RECONSTRUCTION OF LAKE COLERIDGE SUMMER RAINFALL
CALIBRATION PERIOD: 1929 TO 1978, R=0.69
VERIFICATION PERIOD: 1913 TO 1928, R=0.66 RE=0.11
(ALL VALUES ARE TOTAL RAINFALL IN MILLIMETRES)

YEAR	0	1	2	3	4	5	6	7	8	9
1840	105	231	144	159	216	243	90	195	144	198
1850	210	171	135	132	102	105	183	159	189	156
1860	240	231	186	255	213	222	198	210	231	195
1870	180	201	195	198	234	186	234	252	264	198
1880	210	180	174	222	222	81	201	144	183	126
1890	240	207	216	246	204	129	123	210	207	186
1900	240	255	213	141	201	192	150	63	240	279
1910	171	177	198	162	192	213	105	243	219	225
1920	174	168	192	201	111	243	159	126	222	246
1930	201	114	186	144	132	141	249	288	126	231
1940	183	216	204	93	270	276	252	192	231	171
1950	264	225	243	252	207	162	198	312	177	246
1960	240	201	153	258	192	183	144	327	132	159
1970	165	153	192	177	201	165	285	117	150	

RECONSTRUCTION OF HURUNUI SUMMER RIVERFLOW
CALIBRATION: 1956 TO 1978, R=0.77
NO VERIFICATION BECAUSE OF SHORT RECORD LENGTH
(ALL VALUES ARE MEAN DISCHARGE IN HUNDREDS OF LITRES PER SECOND)

YEAR	0	1	2	3	4	5	6	7	8	9
1840	227	690	431	387	564	717	247	649	399	501
1850	631	545	419	330	493	373	531	481	396	473
1860	723	512	380	682	469	544	533	568	655	598
1870	418	604	563	505	656	662	685	407	578	425
1880	487	458	525	657	446	21	622	500	508	356
1890	722	491	598	757	580	305	199	633	662	474
1900	692	689	396	462	740	289	252	219	736	681
1910	510	524	532	421	412	546	512	691	433	498
1920	429	570	546	567	299	514	374	506	649	511
1930	474	245	520	443	330	490	591	736	408	678
1940	494	598	521	201	714	700	616	428	682	417
1950	639	737	715	511	380	321	667	1027	347	687
1960	516	389	454	648	464	528	425	896	627	469
1970	402	307	369	403	555	456	767	475	421	